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ON THE SPEED OF RECURVING TYPHOONS OVER THE WESTERN NORTH PACIFIC--ETC(U)

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ON THE SPEED OF RECURVING TYPHOONS OVER THE WESTERN NORTH PACIFIC OCEAN

Prepared By:

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and the averaged wind speed between 500 and 200 mb, observed, at and 12 hours prior to recurvature, along the future storm track.

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I. INTRODUCTION

One of the most important aspects to typhoon track forecasting is recurvature. Generally speaking, the weather forecaster is most interested in whether a typhoon will move west-northwestward or will recurve toward the northeast. Although the track forecast after recurvature usually has not been given much research attention, it accounts for the largest mean position error. This is mainly due to increasing speed after recurvature. Burroughs and Brand (1973) (noted here as B and B) in a statistical study of recurving typhoons for the period 1961-69 showed that the 24-hour forecast errors increased from 114 n mi for nonrecurving typhoons to 141 n mi for recurving typhoons and further to 165 n mi for forecasts after recurvature. Using a larger data sample, from 1945-69, they determined the seasonal frequencies and areas of recurvature and the relative speeds and directions of movement before and after recurvature and derived multiple regression equations to aid forecasting the speed of movement after recurvature. In addition, they examined synoptic situations during recurvature and devised some "rules of thumb" that related the large-scale circulation to storms with greater or less acceleration than average after recurvature. However, the operational forecasts for recurving storms have not improved. Comparable 24-hour errors for 1978-80 typhoons were 104 n mi for nonrecurvers, 129 n mi for recurvers and 183 n mi after recurving.

This study examines the statistics of recurving typhoons for the period 1970-79 and, through selected case studies, identifies factors which may help forecasting.

(FIGURES 1-28 SHOWN ON PP 28-56)

II. DATA SOURCES

The direction, speed of movement and intensity of typhoons were extracted from the Annual Typhoon Reports (1970-79) of the Joint Typhoon Warning Center (JTWC) at Guam. Selected periods of synoptic charts and additional data were obtained from: (1) Typhoon "data packages" from JTWC, containing the analyzed operational charts for the surface, 700 mb, 500 mb and 200 mb levels, satellite data, fixes, warning messages, etc.; (2) Daily synoptic charts on microfilm from the Royal Observatory, Hong Kong; (3) Daily synoptic charts and tabulated data published by the Japan Meteorological Agency; (4) 500 mb prognostic charts from the Fleet Numerical Oceanography Center (FNOC); and (5) Mean monthly wind charts from Sadler and Harris (1970) and Ramage and Raman (1972).

III. GENERAL FEATURES OF RECURVING TYPHOONS

From the Annual Typhoon Reports (1970-79), we considered typhoons which recurved over the western North Pacific or the South China Sea, excepting those which moved across the mainland of China. There were 71 recurving typhoons during this period.

A. Track Types

The tracks of recurving typhoons can be divided into three types. Examples are shown in Fig. 1. The most frequent track, followed by 50 typhoons, is a regular clockwise parabola. The common characteristic of this type is a rather uniform directional change from west-northwestward to northeastward. The second type is prolonged recurvature. Typhoon movement first changes gradually from west-northwestward to northward for a prolonged period before turning toward northeast. There were ten prolonged recurvatures during this ten-year period. The third type, erratic

movement, comprises two subtypes. In one the typhoon loops at recurvature and remains almost stationary for 2-3 days. In the other the typhoon follows a clockwise or counterclockwise parabolic track as it weakens to less than tropical storm intensity. There were 11 erratic typhoons.

B. Frequency

The monthly distribution of the total typhoons and recurving typhoons during 1970-79 is shown in Table 1.

The 50 typhoons with type one track were combined with the ten type two track typhoons and listed as normal recurvers. The 11 erratic typhoons are listed separately for they could not be used in some of the subsequent statistics. The frequency of recurving tropical storms and typhoons during May-December for the 25-year period 1945-69 from B and B is shown in the last line of Table 1.

Forty-seven percent (71) of the 150 typhoons in our ten-year period recurved over the western North Pacific. Forty-nine (44%) of 112 recurved during the main typhoon season (July-October). Of 22 typhoons in August, 14 (64%) recurved. In spring (March-June), the ratio is highest (12 of 17)--70%.

The frequency of recurvature is significantly different between the ten-year period and the preceding 25 years, particularly for the main typhoon season (July-October). The August and October frequencies switched rankings between the two periods from lowest (34%) to highest (64%) and highest (55%) to lowest (33%), respectively. The frequency of recurvers for the combined months of May-December increased from 40% to 46%. These differences cannot be attributed to the inclusion of tropical storms by B and B for tropical storms have a higher recurvature rate than typhoons. Sixty percent of tropical storms recurved during 1970-79. The

Table 1. Monthly frequency of recurring typhoons for the years 1970-79.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total Sample
Normal recurvers	1		1	5	3	3	6	10	13	10	6	2	60
Erratic recurvers	1						3	4	3				11
Total No. of recurring typhoons	2	0	1	5	3	3	9	14	16	10	6	2	71
Total No. of typhoons	4	1	1	6	4	6	26	22	34	30	11	5	150
% of typhoons recurring 1970-79	50	0	100	83	75	50	35	64	47	33	56	40	47
% of recurring typhoons and tropical storms (Burroughs and Brand)					58	35	20	34	43	55	49	38	40

recurvature rate of typhoons has been particularly high (65%) during the past three years (1978-80).

C. Areal Distribution

Figure 2 shows the distribution of recurvature points for the 71 recurving typhoons. All recurvature points lay north of 12N while in the main typhoon season (July-October) they lay north of 21N with only one exception, at 17N. The envelope of recurvature points moved northward from winter to summer with a sudden shift of about 10° in July-August to its northernmost position. The envelope gradually retreats southward in September-November. The envelope in winter and spring has a bandlike east-west orientation and orients west-southwest to east-northeast in July-November. In the main typhoon season, the recurvature points were concentrated in two areas. Twenty-one typhoons recurved north of the line Taiwan-Okinawa and west of 133E. Among them, 17 occurred in mid-summer (July-August) out of a total of 23 in that period. Nineteen typhoons recurved southeast of Japan within the area 141-153E, 23-40N. Among them, 15 occurred in September-October out of a total of 26 in that period. The separation of recurving points into two areas with a minimum of recurvers between 130E and 140E was not present in the 1945-69 data set of B and B. In fact, in the earlier period recurvers were concentrated between 130E and 140E with a minimum west of 130E.

The typhoon recurvature point envelope and its interseasonal shift are closely related to the mean position of the subtropical ridge line in the middle and upper troposphere. The monthly mean positions of the 500 mb ridge are included on Fig. 2. The mean ridge is essentially vertical from 500 mb through 200 mb during the main typhoon season with only a small northward tilt with height. In winter and spring the ridge

lies near 15-20N. It moves rapidly northward from June to July and reaches its most northern position in August. The retreat southward from summer to fall is more gradual. The ridge tilts slightly west-southwest to east-northeast from August to November. Good correspondence is obvious between the positions of the axis of the recurvature points and the ridge line with the former about 2-4° north of the latter. In other words, in the mean, typhoons recurve near or just north of the mean subtropical ridge line.

D. Maximum Intensity Relative to Recurvature

Riehl (1972), in a statistical study of the intensity of recurving typhoons, showed that in 66 typhoons of 1957-68, 43 (65%) reached maximum intensity within ± 12 hr of recurvature, 22 (30%) reached maximum intensity one day or more before recurvature, and only one reached maximum intensity one day after recurvature. However, our statistics differ (Table 2). Of 60 typhoons, only 24 (40%) reached maximum intensity within ± 12 hr of recurvature, and 14 (23%) reached maximum intensity 18 to 48 hr before recurvature. However, 7 typhoons reached maximum intensity 18 to 48 hr after recurvature and 5 typhoons reached maximum intensity 54 hr or more after recurvature. Also 10 typhoons (19%) attained maximum intensity 54 hr or more before recurvature. Eight of these 10 were supertyphoons (≥ 130 kt).

Table 2. Time lag (TL) of maximum intensity about the recurvature point for the 60 recurving typhoons during 1970-79.

TL (hr)	≤ -78	-72 to -54	-48 to -18	-12 to +12	+18 to +48	$\geq +54$	Total
Frequency	6	4	14	24	7	5	60
Percentage	10	7	23	40	12	8	100%

In this ten-year period there were 31 supertyphoons--17 non-recurving and 14 recurving. Among the latter (Table 3), 13 attained an intensity ≥ 130 kt, then recurved 30 or more hr later. Six of these 13 recurved 78 or more hr later (the longest one was 7 days later). Only one typhoon attained supertyphoon intensity 12 to 24 hr before recurving and none attained this status at or after recurvature. This indicates that supertyphoons generally attain maximum intensity well before recurvature. The reason for this could be that because a supertyphoon is intense and usually large, its inertia of movement is also very large and tends to resist recurvature forces.

Table 3. Time lag (TL) of initial supertyphoon intensity about the recurvature point for the 14 recurving supertyphoons during 1970-79.

TL (hr)	≤ -78	-72 to -54	-48 to -30	-24 to -12	Total
First time for $V \geq 130$ kts	6	2	5	1	14

Table 4. Change in typhoon intensity (V) around the recurvature point for the 60 normal recurving typhoons during 1970-79.

	V decreasing throughout -36 hr to +36 hr about recurvature	V is maximum -12 hr to +12 hr	V increasing throughout -36 hr to +36 hr about recurvature	V is minimum -12 hr to +12 hr	Total
Frequency	24	24	11	1	60
Percentage	40.0	40.0	18	2	100%

The distribution of typhoon intensity changes from 36 hr before to 36 hr after recurvature is shown in Table 4. There were as many typhoons (24%) decreasing in intensity through the period -36 hr to +36 hr about recurvature as there were attaining maximum intensity near recurvature (24%), while 11 typhoons increased in intensity through recurvature. If we take the ratio of intensities at 24 to 36 hr before and after recurvature (R_V) to represent the degree of intensity change, there were 25 (42%) with large decreases in intensity ($R_V < 0.75$), 12 (20%) with large increases ($R_V > 1.38$) and 23 (38%) with little change ($0.75 < R_V < 1.38$).

E. Speed of Movement Relative to Recurvature

Table 5 gives the speed change of typhoon movement within ± 36 hours about recurvature. More than half (52%) of the recurving typhoons were moving slowest at recurvature. Forty percent accelerated while only 7% slowed through the -36 to +36 hour period about recurvature. If we take the ratio of movement speeds (R_C) at 24 to 36 hours before and after

recurvature to represent the acceleration, 40 (67%) experienced large acceleration ($R_c > 1.45$), 8 (13%) large deceleration ($R_c < 0.75$) and 12 (20%), near uniform motion ($0.75 < R_c < 1.45$). Their monthly distribution is shown in Table 6.

Table 5. The speed change of typhoon movement about recurvature for the 60 normal recurving typhoons during 1970-79.

	C increasing throughout -36 hr to +36 hr about recurvature	C is minimum -12 hr to +12 hr	C decreasing throughout -36 hr to +36 hr about recurvature	C is maximum -12 hr to +12 hr	Total
Frequency	24	31	4	1	60
Percentage	40	52	7	2	100%

Table 6. Monthly distribution of moving speed change types during the -36 hr to +36 hr period for the 60 normal recurving typhoons during 1970-79.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Accelerating	1		1	2	2		4	6	10	8	4	2	40
Decelerating				1	1	2	2		1	1			8
Uniform				2		1		4	2	1	2		12

Table 7. The average movement speed (kts) distribution within three days about recurvature point, in 6 hr and daily increments, for the 40 accelerating and eight decelerating recurring typhoons during 1970-79. Data sample when less than total sample is shown in parentheses.

Time (hr)	-72	-66	-60	-54	-48	-42	-36	-30	-24	-18	-12	0	6	12	18	24	30	36	42	48	54	60	66	72
6 hr average	10 (32)	9 (34)	9 (38)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	11 (36)	16 (36)	22 (36)	22 (36)	24 (15)	26 (29)	26 (29)	26 (29)	24 (15)	24 (15)	18 (7)	18 (7)	18 (7)
ty-phoons (40)	9 (32)	9 (37)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	13 (39)	19 (39)	19 (39)	24 (32)	24 (32)	25 (19)	25 (19)	23 (9)	23 (9)	20 (7)	20 (7)	20 (7)	20 (7)
Daily Average	9 (32)	9 (32)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	9 (39)	15 (36)	15 (36)	15 (36)	15 (36)	24 (15)	24 (15)	24 (15)	24 (15)	24 (15)	21 (7)	21 (7)	21 (7)	21 (7)
6 hr average	9 (7)	10 (7)	10 (7)	11 (7)	11 (7)	12 (7)	12 (7)	12 (7)	12 (7)	10 (7)	8 (7)	6 (7)	6 (7)	6 (7)	5 (7)	5 (7)	7 (7)	7 (7)	7 (7)	6 (6)	6 (6)	16 (6)	16 (6)	16 (6)
ty-phoons (8)	10 (7)	11 (7)	11 (7)	12 (7)	12 (7)	12 (7)	12 (7)	12 (7)	12 (7)	10 (7)	8 (7)	6 (7)	6 (7)	6 (7)	5 (7)	5 (7)	9 (6)	9 (6)	9 (6)	13 (6)	13 (6)	14 (5)	14 (5)	14 (5)
Daily average	10 (7)	10 (7)	10 (7)	12 (7)	12 (7)	12 (7)	12 (7)	12 (7)	12 (7)	8 (7)	8 (7)	6 (7)	6 (7)	6 (7)	5 (7)	5 (7)	7 (7)	7 (7)	7 (7)	14 (5)	14 (5)	14 (5)	14 (5)	14 (5)

The average speeds of movement within ± 3 days of recurvature in 6-hour and daily increments are shown in Table 7 for the 8 decelerating and 40 accelerating typhoons. The sample size decreases rapidly for accelerating typhoons at times greater than 36 hours after recurvature and only 7 tracks were carried to 72 hr after recurvature. Therefore the indication that the moving speed of accelerating typhoons peaks near 36 hr after recurvature is probably not real but due to sample bias. The total sample, although small, indicates that decelerating typhoons tend to have a greater speed of movement than accelerating typhoons at periods of 1-3 days before recurvature.

F. Discussion

The differences in the statistical parameters of this data set compared to those used by B and B and Riehl emphasize that climatology can furnish only the gross bounds of the forecast parameters. As B and B did, we also examined synoptic patterns during the recurvature of accelerating and decelerating typhoons in the September-November period in search of some general forecasting "rules of thumb." For this we used the published 500 mb analyses of the Japan Meteorological Agency. The results were not significantly different from B and B's which were based on the 700 mb level. However we think that lower levels, even 500 mb, are not as good as 250 or 200 mb for case studies of anomalous and hard to forecast typhoons. This reasoning is based on the facts that not only do sparse data at 700 and 500 mb prevent adequate analyses, but that the lower levels do not reflect the complexity of the upper troposphere in the western Pacific. During the main typhoon season from July-October,

a double ridge system (subequatorial and subtropical) separated by the tropical upper tropospheric trough (TUTT) dominates the region. However, this study is not concerned with devising general rules but is directed toward the specific problem of typhoon acceleration after recurvature.

IV. CASE STUDIES OF TYPHOONS WHICH ACCELERATED AFTER RECURVATURE

A. History of Selected Typhoons

Three 1979 typhoons were selected for study. Typhoon Irving in August, Owen in September and Tip in October rapidly accelerated after recurvature, leading to greater than average forecast errors. Spanning a period from mid-August to mid-October, they were ideal for study since a seasonal influence could be evaluated. Their differing histories are shown in Figs. 3-5 and Table 8.

Table 8. Typhoon histories.

Typhoon	Irving	Owen	Tip
Recurving time	00Z Aug 16	00Z Sept 29	18Z Oct 17
Recurving position	30°N, 124°E	28°N, 130°E	24°N, 128°E
V_{\max}	90 kts	110 kts	165 kts
Time lag of V_{\max} to recurvature	-6 hr	-72 hr	-132 hr
Average speed \bar{C}_b for 4 days before recurvature	8.3 kts	5.8 kts	6.7 kts
Average speed \bar{C}_a for 42 hours after recurvature	23.6 kts	24.5 kts	34.5 kts
\bar{C}_a/\bar{C}_b	2.84	4.22	5.15

Irving was relatively weak (90 kts); Owen was of moderate intensity (110 kts); and Tip was a supertyphoon (165 kts) with the lowest sea level pressure and largest circulation diameter on record (Dunnavan and Diercks, 1980). Irving recurved near time of maximum intensity, Owen three days after, and Tip more than five days after. Irving did not begin to accelerate until some 18 hours after recurvature. Owen's acceleration began within six hours of recurvature and Tip was already accelerating at recurvature. The rate of acceleration, measured by the ratio of the average speed during four days before recurvature to that for 42 hours after recurvature (\bar{C}_a/\bar{C}_b) shows that Tip (5.15) accelerated faster than Owen (4.22) and both accelerated much faster than Irving (2.84). The recurvature tracks were also quite different. Irving had a prolonged path to the NNW and recurved gradually; Owen also underwent prolonged recurvature but had two recurvature points (the most northern one is the defined recurvature point); and Tip's track was a classic parabola.

Initially we screened and studied the material available from JTWC--analyses, forecasts, prognostic reasonings, objective forecasts, etc.--to determine the major forecast problems with the three typhoons and to reexamine the recurvature periods for any synoptic clues that may have been overlooked or misanalyzed under operational pressure and time limitations.

B. Forecast Errors Relative to Recurvature

Judged by the 24-hour forecast errors, forecasting for all three typhoons was more difficult than average. The average error for all tropical cyclones in 1979 was 124 n mi compared to 163, 146 and 135 for Irving, Owen and Tip, respectively. All three had above average forecast errors during the initial four or five days due to long anomalous tracks while still depressions or tropical storms (Figs. 3-5); however, the

largest errors were made after recurvature (Table 9).

The large errors were due mainly to acceleration because JTWC forecast the recurvature paths very well. Irving did not begin to accelerate until 18 hours after recurvature and the errors were below average for the 24-hour forecast made at and 6 hours after recurvature. The errors for Owen were also below normal for the first two forecasts after recurvature because it was moving slowly. Tip accelerated through recurvature; the large forecast error of 289 n mi made at recurvature time was more than twice the error of the forecast made 12 hours earlier.

The "jogs" in the long northerly tracks of Irving and Owen produced some false recurvature forecasts with a few moderately large forecast errors. As discussed earlier, the circulation in the upper troposphere appears to be best related to the tracks. Figure 6 is the 200 mb analysis (after JTWC) at 12Z on 13 August near the beginning of Irving's northerly movement and when the first JTWC recurvature forecast was made. Irving, at 22N, had passed through the subequatorial ridge (SER) and was located between the latitudes of the SER and the TUTT with westerly flow to the east. However, although the subtropical ridge (STR) was in its normal latitude of 30N over China, both the TUTT (33N) and STR (38N) near Japan were north of normal. A storm located between the SER and the TUTT usually drifts northwestward (Sadler, 1976). Irving finally recurved at 30N on the 16th after the TUTT and western Pacific segment of the STR had retreated southward to their normal positions.

The 200 mb circulation at the first recurvature point of Owen (Fig. 7) was different from that described above for Irving. The STR over China had undergone its normal seasonal shift southward to near 22N by 27 September and Owen began to recurve on passing through this latitude;

Table 9. 24-hour forecast errors (n mi) at and after recurvature for typhoons Irving, Owen and Tip.

IRVING		OWEN		TIP	
Forecast made at	Error	Forecast made at	Error	Forecast made at	Error
16/00Z	39	29/00	82	17/18	289
16/06	68	29/06	84	18/00	330
16/12	219	29/12	197	18/06	431
16/18	285	29/18	331	18/12	539
17/00	291	30/00	417	18/18	422
17/06	<u>362</u>		---		---
Average	211		222		404
Average error for total lifetime	163		146		135

however, the western Pacific branch of the STR, north of the TUTT, was near 29N and Owen turned slightly back to the north and did not recurve until crossing the latitude of this ridge on the 29th.

During the recurvature period of Tip, the upper tropospheric circulation was more simple than for either Irving or Owen. By mid-October the TUTT had receded eastward of 150E and the STR had moved southward to 24N over the western Pacific southeast of Japan and tilted southwestward to link smoothly with the STR over east China near 21N. Tip executed a near-perfect parabolic recurve path centered at 24N on the 17th.

The subjective track forecasting of Irving and Owen using satellite pictures was discussed by Bao (1981).

C. Evaluation of Some Forecast Aids

The Fleet Numerical Oceanography Center (FNOG), using a tropical cyclone model (TCM) with interactive boundary conditions provided forecasts for operational testing at JTWC during the 1979 typhoon season. Typhoons Irving, Owen, and Tip were positioned within the densest available data during and after recurvature and therefore ensured optimum evaluation of the model performance. TCM forecasts, available at 12-hour intervals, are compared to JTWC forecasts in Table 10.

Table 10. Evaluation of FNOG objective forecasts and B and B statistical forecasts.

	Average error of 24-hr forecast made nearest re- curvature time and 12 hr later		Average 24-hr error for sub- sequent fore- casts		Speed (kts) at 36 hrs after recurvature	
	JTWC	TCM	JTWC	TCM	Observed	B&B fcst
Irving	129	193	291 (1)*	393	23	23
Owen	61	116	232 (3)	351	15 (5)**	5 (12)
Tip	145	202	338 (1)	502	48	24

*Number of comparable forecasts.

**First recurvature point at 00Z 26 September (see Fig. 4).

The model forecast errors greatly exceeded those of JTWC for every forecast during and after recurvature.

The material received from JTWC did not reveal that the forecast speed of typhoons at 36 hours after recurvature are routinely determined using the statistical regression equations of B and B. Our forecasts

using the equations are compared to the observed speed in the last columns of Table 10. The forecast for Irving was good but those for Owen and Tip were much too slow.

D. Upper Tropospheric Flow and Typhoon Acceleration after Recurvature

1. 200 mb flow patterns

Large forecast errors after recurvature, such as occurred with Typhoons Irving, Owen, and Tip, are likely to be first attributed to a failure to forecast conditions west of the recurvature longitude. This involves the movement and/or the deepening of an upper tropospheric trough which greatly accelerates the southwesterly flow over and around the filling typhoon and causes it to rapidly accelerate.

A study of the JTWC 200 mb analyses and an evaluation of the FNOC 12, 24, 36, and 72 hour 500 mb wind forecasts showed definitely that such a forecast error was not a factor. No significant trough formed in or moved across the region during the periods of the typhoons. This is confirmed in Figs. 8-10 by the positions and orientations of the jet stream axis for two to three days before and after recurvature. Allowing for the normal southward seasonal shift of the jet from August to October, the position and time changes of the jet axis with respect to the typhoons were similar. During the three days prior to recurvature a slight ENE to WSW tilt of the jet axis remained unchanged as did the position of the jet maximum speed northwest of the typhoons (shown by the solid triangles on the jet axis). Also, the latitude of the 200 mb ridge over east China changed very little (Table 11). Obviously no trough perturbations traversed the area to the west of the typhoons during the three-day period prior to recurvature.

Beginning near recurvature time the jet axis rotated counter-clockwise, shifting slightly southward west of the typhoons and northward

to the north and east of the typhoons. The typhoons moved parallel to the jet axis after recurvature. The change in orientation of the jet axis during recurvature was not due to a transient trough in the westerlies but to the effect of the typhoons which will be noted later in discussions of the 500-200 mb thickness patterns.

Table 11. Variation in latitude of 200 mb jet stream and subtropical ridge over east China during the three days before typhoon recurvature.

Typhoon	Irving	Owen	Tip
Recurving latitude θ_0	30N	28N	24N
Latitude of 200 mb ridge θ_1	27-29N	22-24N	20-21N
$\theta_1 - \theta_0$	-1 to -3° Lat	-4 to -6° Lat	-3 to -4° Lat
Latitude of 200 mb jet stream θ_2	41-43N	36-37N	33-34N
$\theta_2 - \theta_0$	11 to 13° Lat	8 to 9° Lat	8 to 9° Lat

Since no major transient systems in the westerlies were involved in the forecasts of these three typhoons, we investigated the structure of the upper troposphere to the north of the typhoons with emphasis along the future tracks. The typical wind profiles in the vertical along the typhoon track can be roughly classified into three types as shown in Fig. 11. The first (refer to area A of Fig. 11) is associated with the typhoon circulation in the tropics. The wind is strongest near the surface and sharply decreases with height while the wind direction changes very little. The second type (area B) is associated with the subtropical ridge. An easterly component in the lower layers underlies a westerly component while speeds are normally moderate in both

layers with a relative minimum in the transition zone. The third type (area C) is observed in the higher latitude westerly wind belt. A westerly wind increases rapidly with height.

The influence of the environmental wind field changes as the typhoon recurves and moves northward. While south of the ridge, and within the tropics, the typhoon dominates the circulation for a considerable radius and throughout the depth of the troposphere. As it moves northward through the ridge, usually at a weakness or break in the ridge, the typhoon is usually weakening; perhaps of greater importance the depth of the closed circulation decreases from the top. As it moves into the westerlies, while continuing to decrease in intensity and depth, the typhoon is engulfed by the environmental westerlies and its closed circulation is restricted to the lower troposphere. These rapid after-recurvature changes in typhoon dimensions and the increasing influence of the environmental flow on vortex movement, while important to the forecast problem, cannot be measured and furnished as an aid to the forecaster. However, since the influence of the storm in altering the surrounding environment decreases with time after recurvature, the large-scale environment was analyzed around the times of recurvature to determine its space and time distribution and variability along the tracks of Irving, Owen, and Tip.

2. 500-200 mb thickness

The warm cored typhoon transports large amounts of latent heat of condensation to the middle and upper troposphere. As a result the isobaric surfaces are inflated and a ridge develops at these levels. Maximum transport northward on the east side of a typhoon builds the ridge toward the northeast. We used the height difference between 500 and 200 mb to indicate the mean temperature structure in the middle to upper troposphere.

Figure 12 shows an analysis of the thickness field at 00Z on 28 September just before Typhoon Owen recurved. The thickness center over the typhoon and the ridge to the northeast are prominent features. Note that the future track of Typhoon Owen was along the thickness ridge. However, caution is advised in using this feature as a forecast aid for such good correspondence is not always observed. The thickness center and a ridge oriented to the northeast were also prominent features associated with Typhoons Irving (Figs. 13 and 14) and Tip (Fig. 15) near recurving time; however, their future tracks were not always in the direction of maximum ridging. However, the forecaster should keep in mind and account for the effect of the ridging in rotating the jet axis to a more southerly direction north of the typhoon, as illustrated in Figs. 8-10. We found no persistent feature in the thickness patterns to aid in the forecast of a typhoon's speed after recurvature.

3. 850-200 mb wind shear

We next examined the distribution of shear in the vertical around and to the north of the typhoons. Figures 16-21 are analyses of the shear from 850 to 200 mb near the time of recurvature of the typhoons. The patterns of shear direction shown by the streamlines are quite similar. Anticyclonic shear is associated with each typhoon and westerly shear is observed to their north. The patterns are quite stable over the 12-hour span between analyses.

Outside of the region dominated by the typhoon (within the dotted line), the pattern and magnitude of the shear are also stable over the 12-hour span between analyses; however, there is a large difference between typhoons. North of Typhoon Irving a field of minimum shear separates the typhoon associated maximum from the jet stream maximum (Figs. 16 and 17). Irving accelerated very slowly for the first 24 hours after

recurvature. The jet stream shear maximum merged with the typhoon associated maximum for both Owen (Figs. 18 and 19) and Tip (Figs. 20 and 21) with a large southward-directed gradient but both the magnitude and the gradient of the shear were greater for Tip. After recurvature Tip accelerated more rapidly than Owen and attained a higher forward speed.

There appears to be some after-recurvature forecast value in an analysis of the shear field; however, north of the subtropical ridge line the greatest contributor to the 850 to 200 mb shear is the wind at the high levels; therefore, the wind field in the upper troposphere should be as good or perhaps better than the shear field as an aid to forecasting.

4. 500-200 mb averaged wind speeds

The above was tested by analyzing the wind speeds averaged from 500 to 200 mb at recurvature time and at 12 hours before and after recurvature. The analyses at recurvature are shown in Figs. 22-24. (The pattern at 12 hours before and after were quite similar.) Subjectively these speed patterns have a better relationship to the future movement of the typhoons than do the wind shear patterns.

North of Irving (Fig. 22) a narrow minimum speed zone of less than 20 kts existed between 34 and 39N and reached only 45 kts at 45N. Irving accelerated slowly for the first 36 hours (Fig. 3) to a maximum of 32 kts before being dropped as a depression at 45N. At the recurvature time of Owen the averaged wind analysis (Fig. 23) showed a jet stream maximum along 40N and the wind along Owen's future track ranged from 30 kts at 33N to almost 80 kts at 40N. Owen accelerated rapidly north of 30N (Fig. 4) to 47 kts before being dropped as a depression at 40N. At the recurvature time of Tip (Fig. 24) an averaged jet core of near 70 kts crossed the future track near 36N. North of the jet core a relative minimum speed zone of less than 40 kts crossed the track at 41N. Tip's

moving speed history (Fig. 5) corresponded quite well to this pattern-- rapidly acceleration from 10 kts at recurvature to a maximum of 55 kts in the jet core region beginning at 35N and then slowing to 42 kts in the minimum wind speed zone north of 40N.

For all three typhoons there appears to be a useful forecasting relationship between the distribution of the upper tropospheric wind speeds at recurvature time and the subsequent movement of the typhoon. To better define this relationship we plotted the moving speed of the typhoon and the 500-200 mb average upper tropospheric winds along the typhoon track (Figs. 25-27). Owen and Tip traversed the data-rich area of Japan and fixed station data were used. Irving remained over the sea for most of the time after recurvature; therefore, wind speeds were extracted from analyses of the Japan Meteorological Agency and the Royal Observatory, Hong Kong. The average wind over the layer from 500 to 200 mb was also averaged in time for three different intervals: (1) At and 12 hours prior to recurvature; (2) at, 12 hours and 24 hours prior to recurvature; and (3) 12 hours and 24 hours prior to recurvature. (The southern positions of the wind speed curves are dominated by the typhoon circulation and are shown thinner.) The curves at the three different time intervals are very similar, indicating that the large-scale wind field was stable for each typhoon around the recurvature time. The only exception was the slight northward shift of the minimum-maximum pattern north of Tip between 12 to 24 hours and 0 to 12 hours prior to recurvature. The close relationship of the future movement of the typhoons after recurvature to the observed upper tropospheric wind field at and before recurvature is rather remarkable. The best overall correspondence is with the averaged observations at and 12 hours before recurvature. A movement forecast of 10 kts less than the

observed wind speeds at these times would have produced an excellent forecast within ± 5 kts of the observed movement for all three typhoons. These results would seem to warrant a further effort in testing a larger sample of past typhoons. Further positive results should be field tested. Forecast wind fields should also be tested. Only the FNOC 500 mb wind forecasts were tested using diagrams similar to those of Figs. 25-27. The results were poor. In addition we would suggest that, since most typhoons do not traverse a good observational network, the vertically averaged winds could be replaced by data extracted from a good 250 or 200 mb wind analysis which uses a composite of all wind observations from observing stations, aircraft and satellites.

E. The Real-Time Test of a Forecast Aid

The opportunity arose for a real-time test of the last suggested aid during Typhoon Gay in October 1981. Our only aids were copies of the 12 hourly 250 mb wind analyses from the National Meteorological Center and the surface analyses from the Honolulu Forecast Center. The one-time forecasts were made at the first anticipation of recurvature at 12Z on 20 October and extended in 12 hr increments until the forecast position crossed 40N, which for both of our independent forecasts was near 60 hr. The JTWC forecast was used for comparison. Their forecast positions for 12, 24, 48 and 72 hr were taken from the surface chart as were the subsequent positions of Gay; therefore, the positions are approximate and subject to the errors of plotting and extraction from the map. The forecast positions are shown in Fig. 28 and listed in Table 12. Our forecasts anticipated the acceleration of Gay quite well while the JTWC forecast was much too slow, particularly beyond 36 hr.

Table 12. Forecasts for Typhoon Gay made at 12Z 20 October 1981.

Forecast length	Verifying date time	LATITUDE			LONGITUDE		
		Bao	Sadler	JTWC	Actual	Bao	Sadler JTWC Actual
12 hr	21/00	24.5	24.5	24.2	24.6	128.0	128.0 127.9 128.8
24 hr	21/12	26.5	27.0	26.3	26.9	128.0	128.3 127.6 130.0
36 hr	22/00	30.0	31.0	28.2*	28.5	129.0	131.5 129.3* 133.2
48 hr	22/12	36.0	36.4	30.2	33.0	135.0	139.5 131.0 137.5
60 hr	23/00	41.0	41.3	32.3*	40.0	143.0	147.5 136.5* 147.0
72 hr	23/12			34.5	49.0		142.0 155.0

*Interpolated values

NOTE: JTWC and actual values are only approximate since they were positions extracted from an ozalid copy of the operational surface chart from the National Weather Service, Honolulu.

V. SUMMARY

Western North Pacific tropical cyclone data were evaluated for the period 1970-79 to determine characteristics of the recurving typhoons near and after recurvature. Some of the characteristics differed from those reported by Burroughs and Brand (1973) and Riehl (1972) in studies of earlier data sets.

Typhoons Irving, Owen and Tip, all occurring in 1979, were selected for case studies to search for factors or relationships which can aid in the forecast of movement speed after recurvature. Each accelerated after recurvature and produced greater than average forecast errors; however, the typhoons differed in time of occurrence, maximum intensity, size, speed of movement, latitude and longitude of recurvature and rate of acceleration after recurvature. Analyses of the upper troposphere within \pm three days of their recurvature revealed that: (1) a moving or developing trough in the midlatitude westerlies was not a significant factor in their history during or after recurvature; (2) the heat export from each typhoon produced ridging to the northeast which caused a counterclockwise rotation in the orientation of the jet stream in the westerlies north of the typhoon near the time of recurvature; (3) common to all three typhoons was a good relationship between the speed of movement after recurvature and the observed upper tropospheric wind speed at and before recurvature averaged between 500 and 200 mb along the subsequent track. A variation of this last finding--using only the observed winds at 250 mb--was tested in a real-time forecast for Typhoon Gay in October 1981. The observed acceleration of Gay after recurvature was forecast quite well at the time of recurvature.

Acknowledgments

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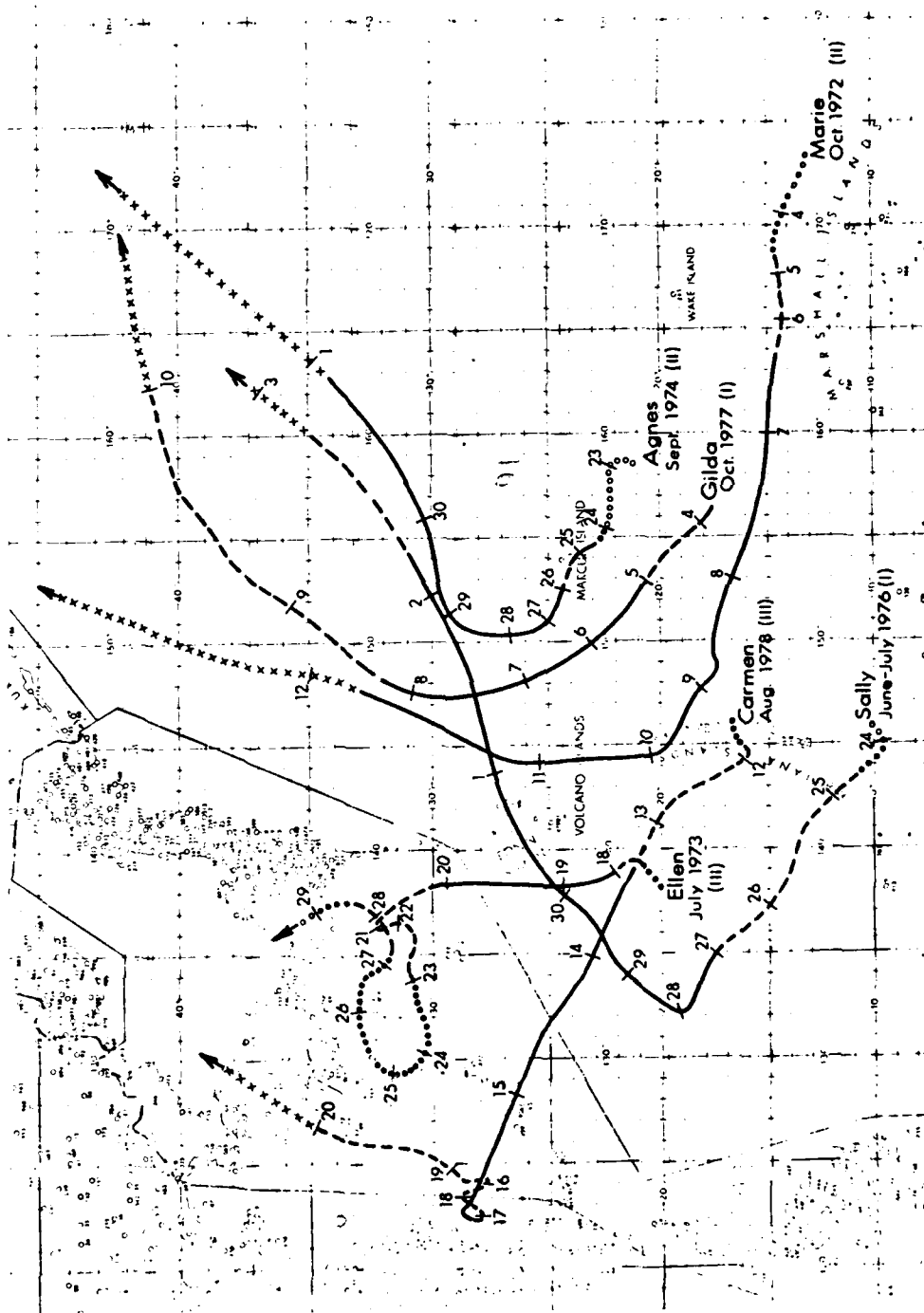


Fig. 1. Illustration of three common types of recurring typhoon tracks. See text for discussion of types.

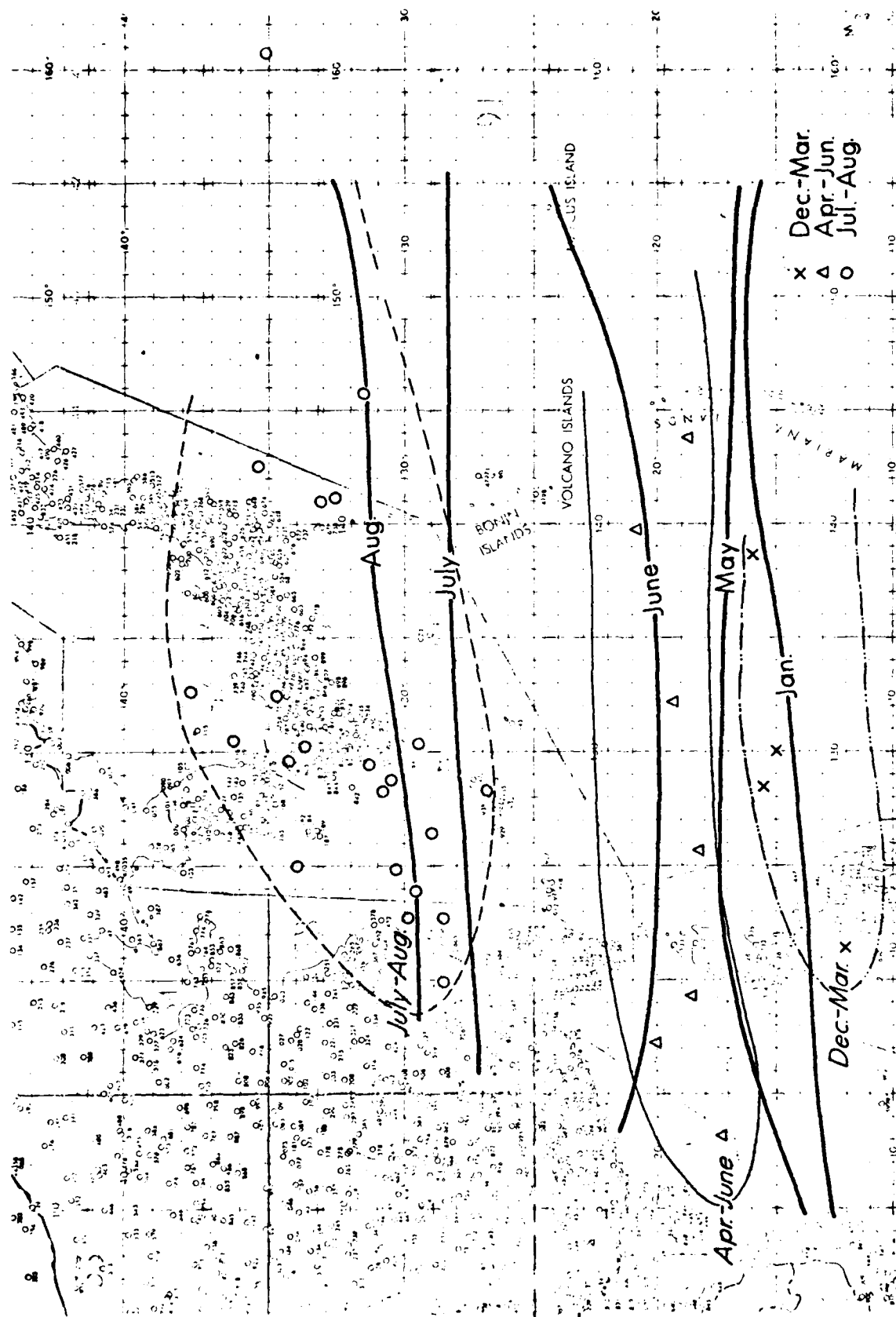


Fig. 2. Distribution of typhoon recurvature points for the period 1970-79. Thin lines--envelope of recurvature points. Thick lines--monthly mean positions of 500 mb subtropical ridge.

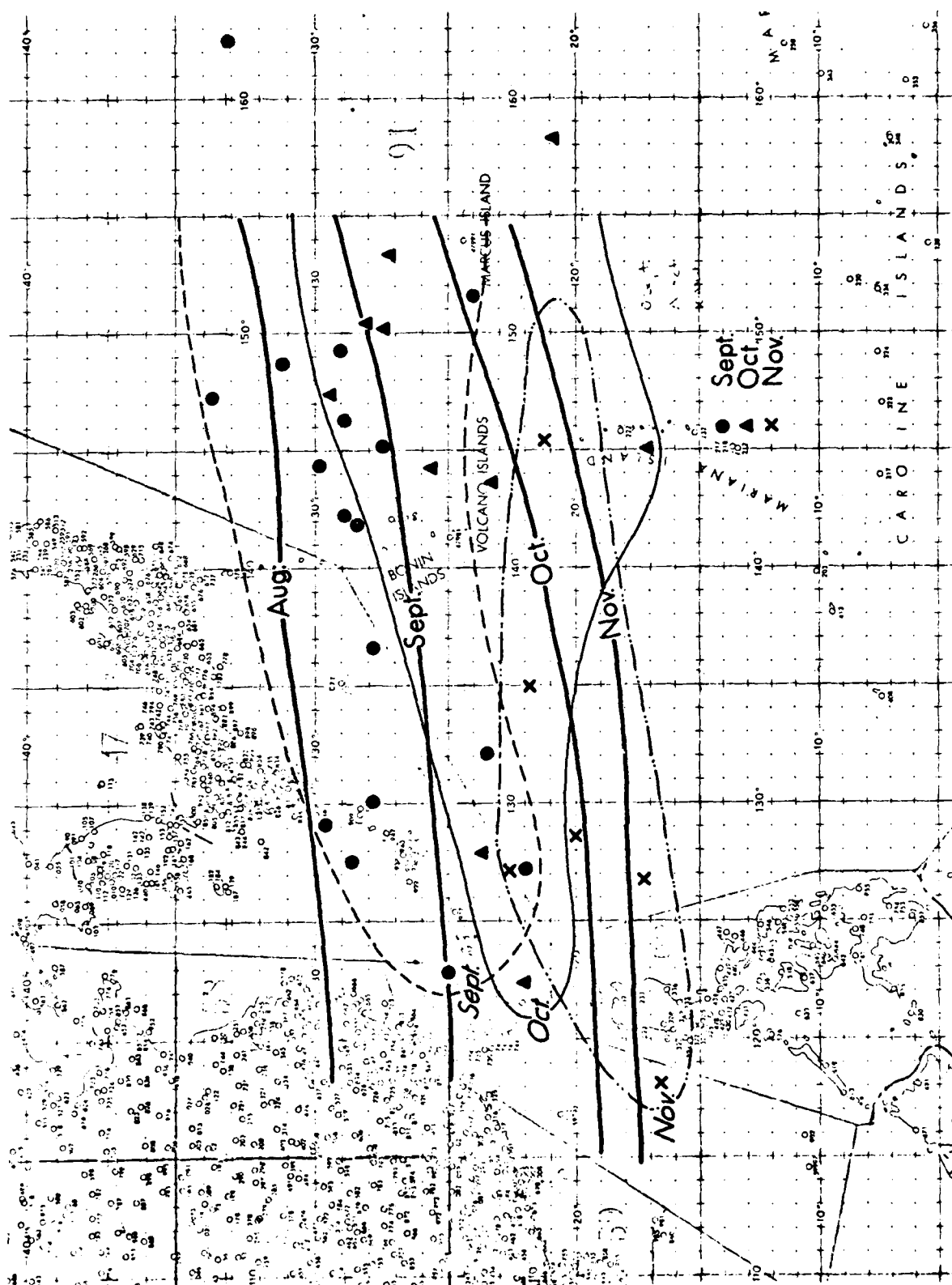


Fig. 2. Continued

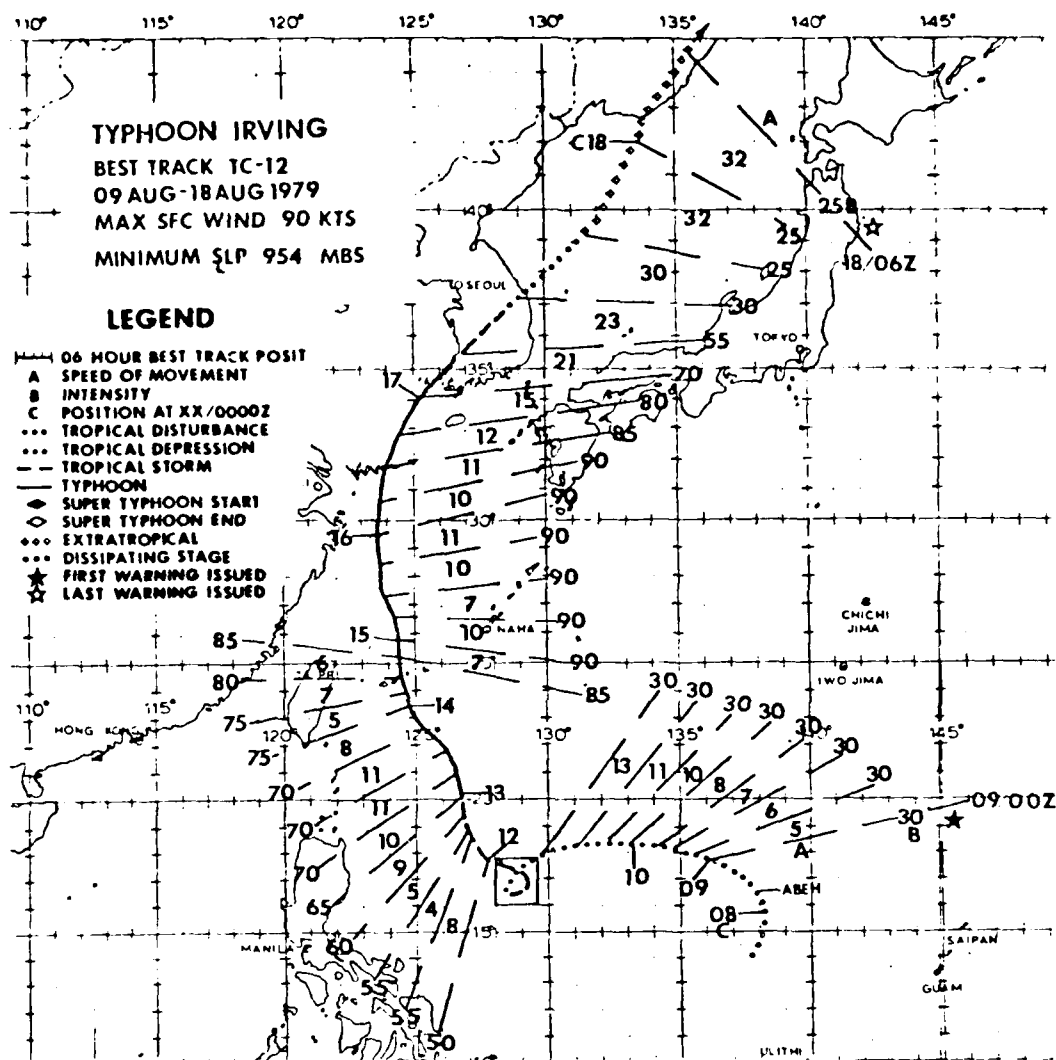


Fig. 3. Typhoon Irving track, intensity (kt) and speed of movement (kt).
 (From JTWC, 1979).

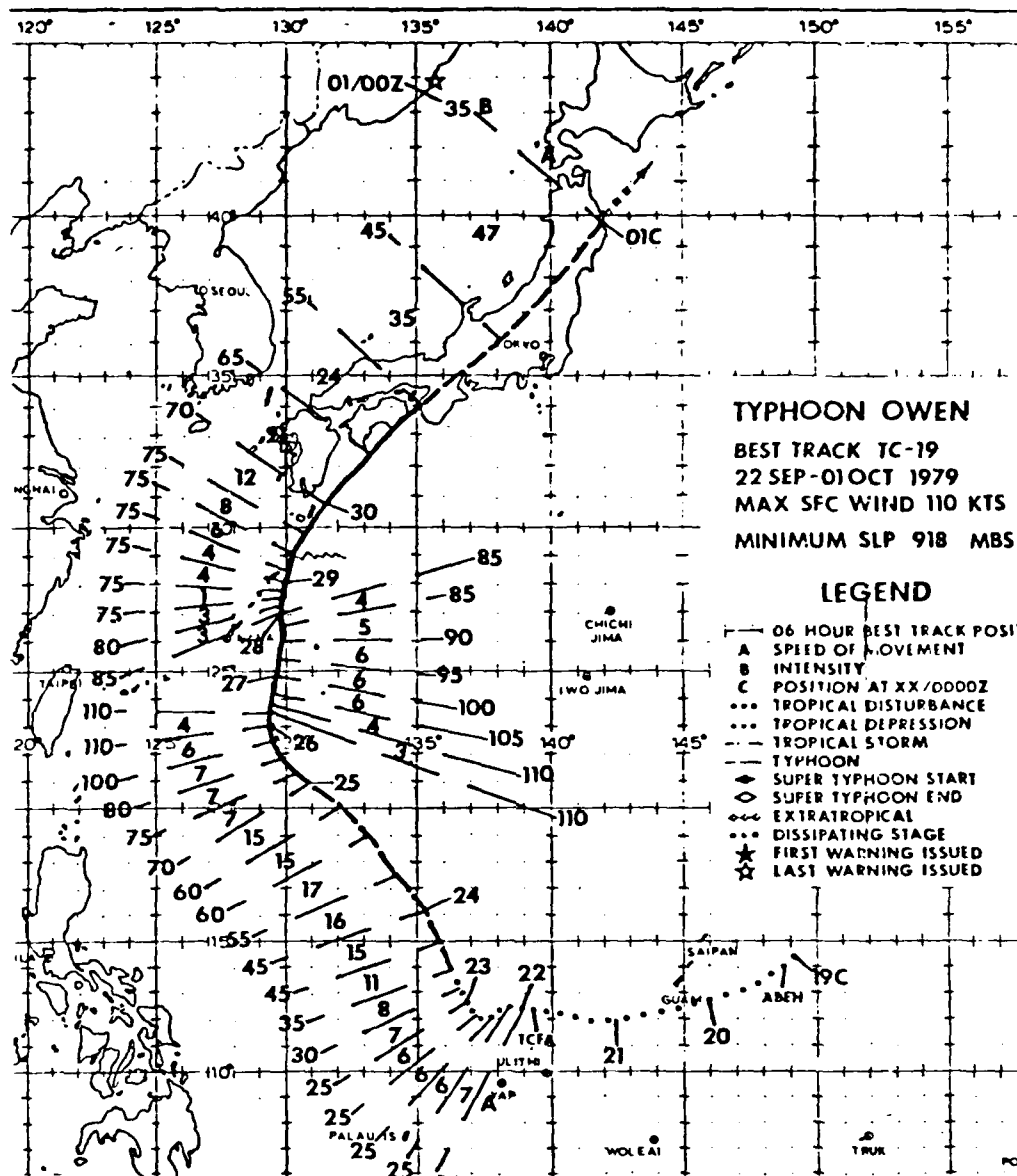


Fig. 4. Same as Fig. 3 except for Typhoon Owen.

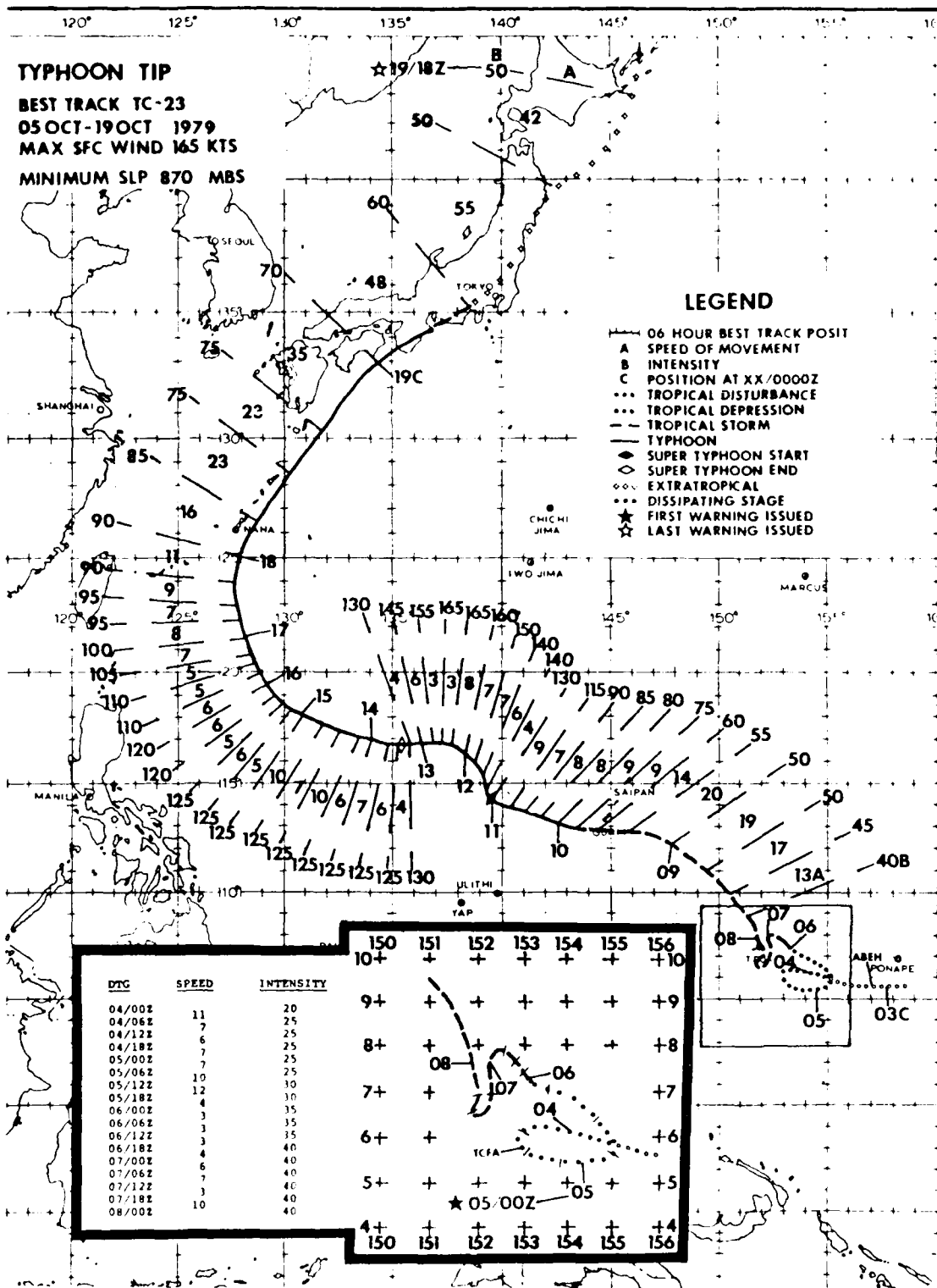


Fig. 5. Same as Fig. 3 except for Typhoon Tip.

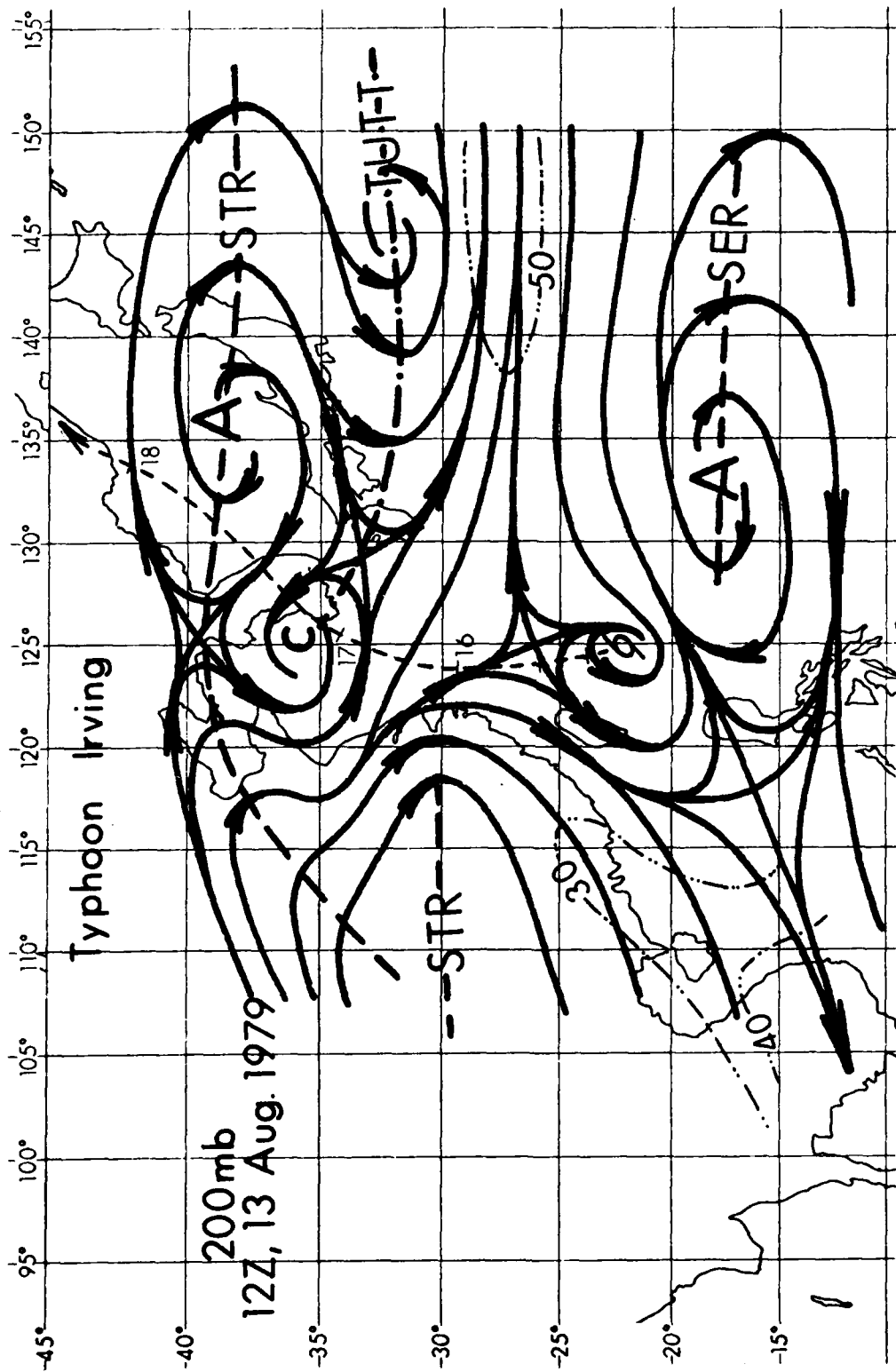


Fig. 6. 200 mb streamline analysis at 12Z, 13 August (after JTWC). Wind speed in kt. Position of Irving shown by tropical cyclone symbol.

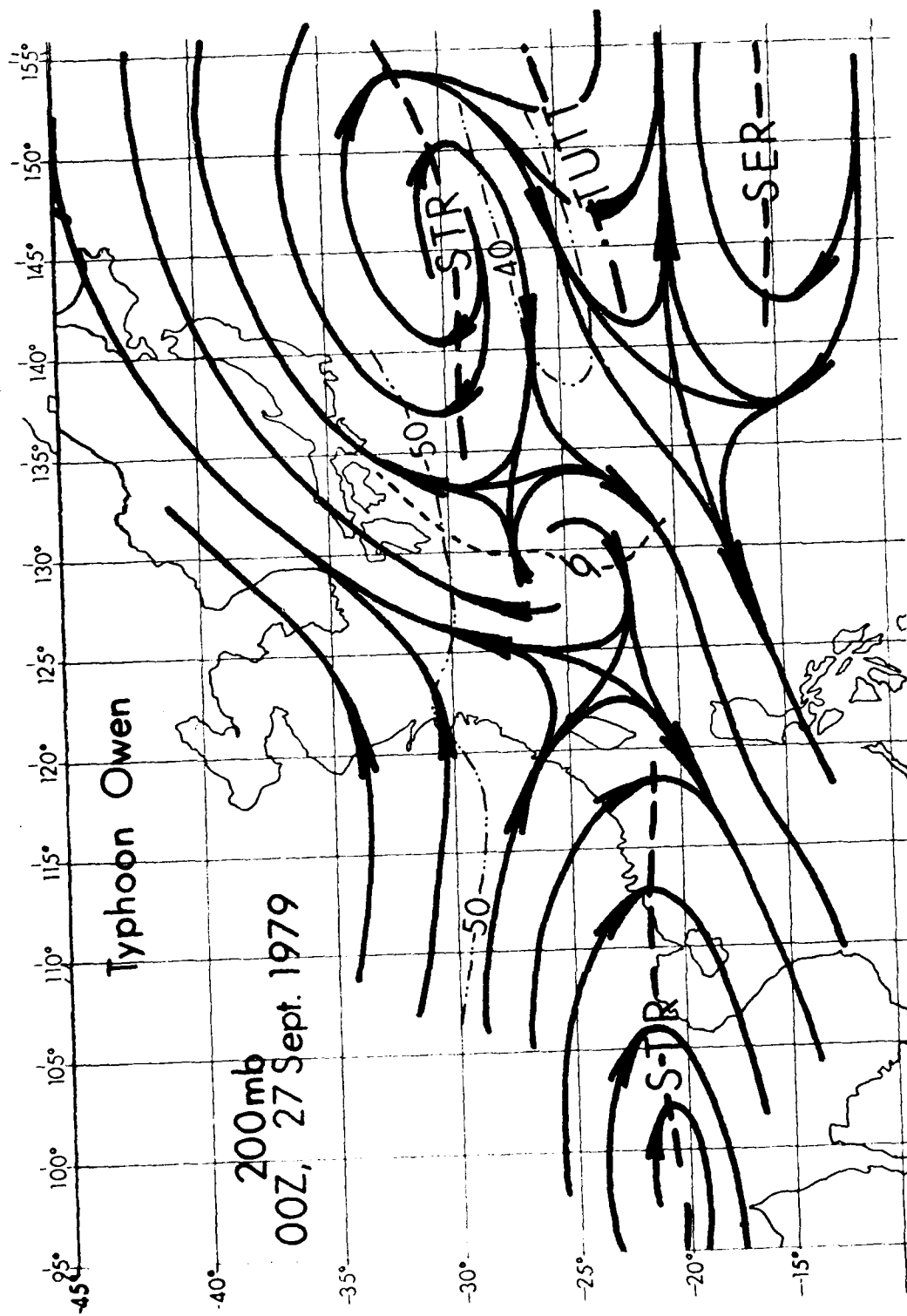


Fig. 7. 200 mb streamline analysis at 00Z, 27 September (after JTWC). Wind speed in kt. Position of Owen shown by tropical cyclone symbol.

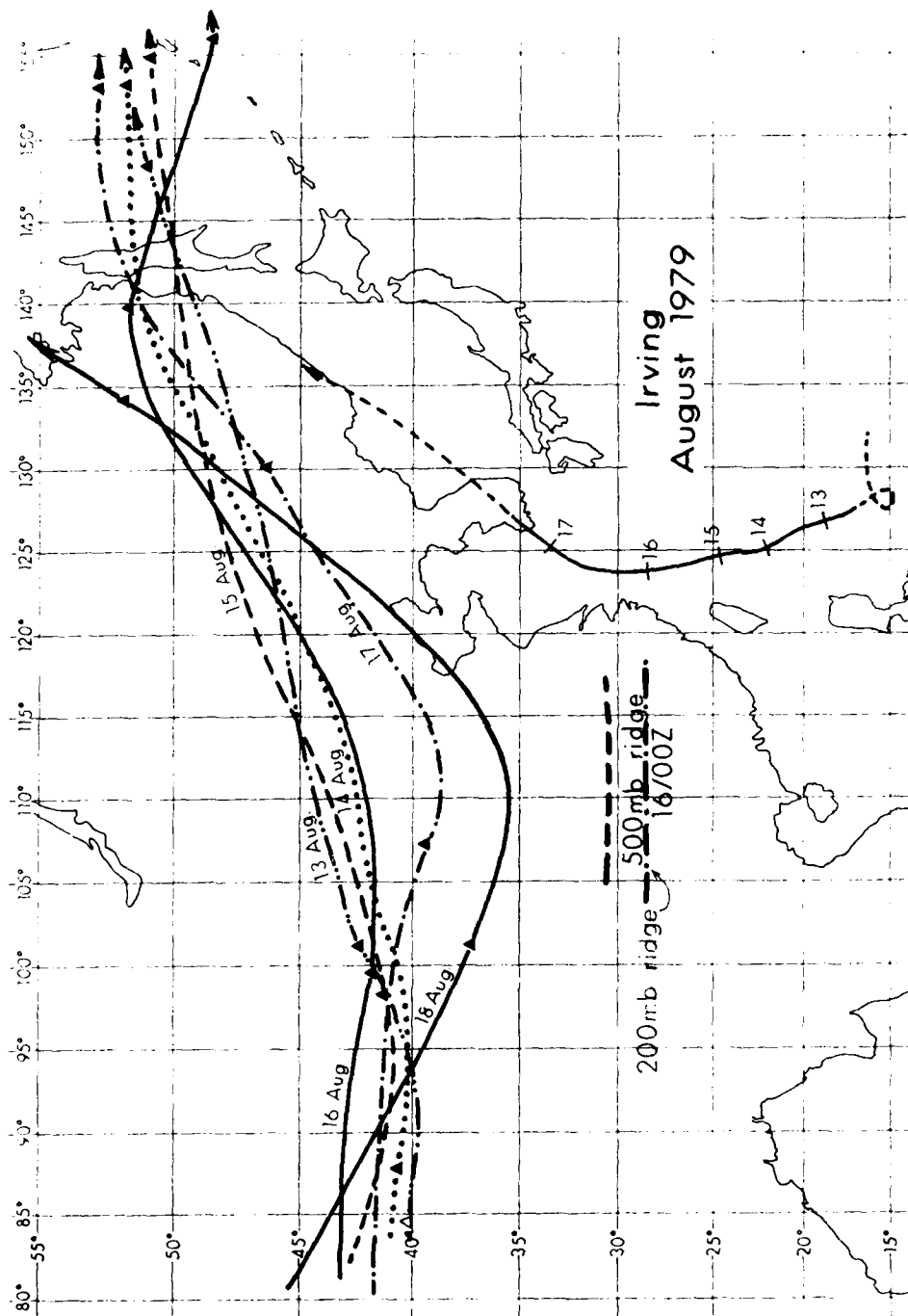


Fig. 8. The positions of the maximum wind core at 200 mb during the period of three days before, during and two days after the recurvature of Typhoon Irving. Solid triangles are positions of maximum wind centers along the core.

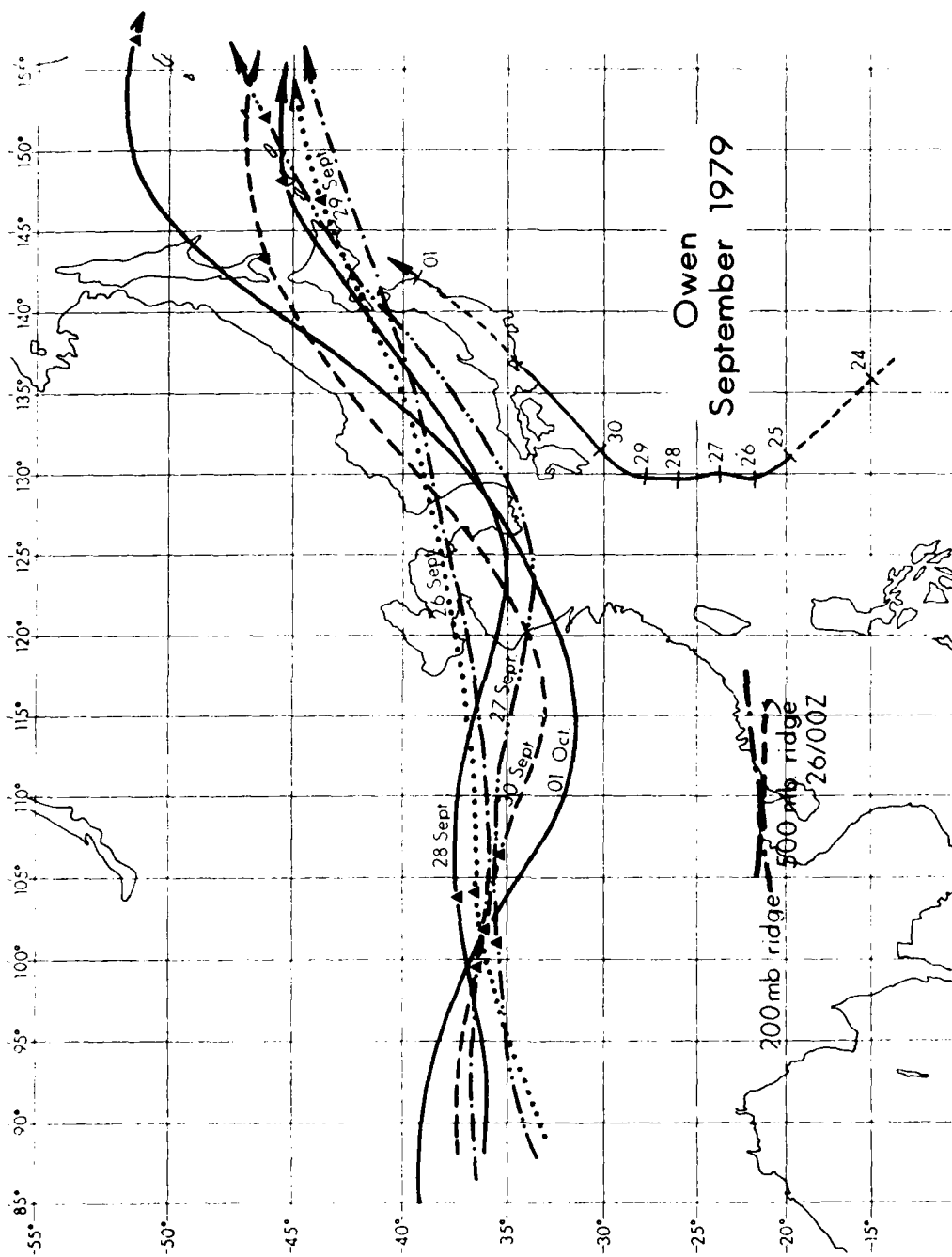


Fig. 9. Same as Fig. 8 except for Typhoon Owen.

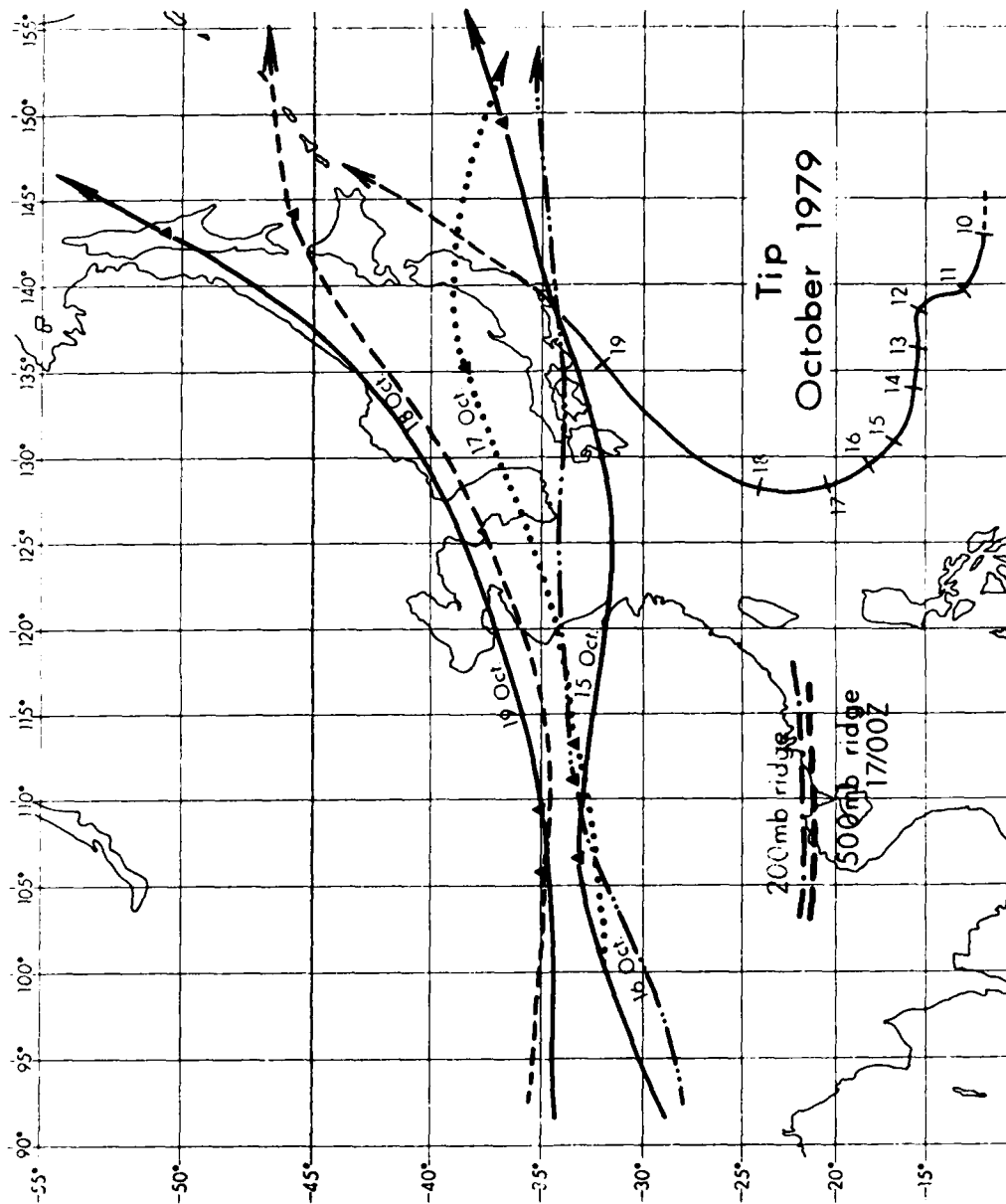


Fig. 10. Same as Fig. 8 except for Typhoon Tip.

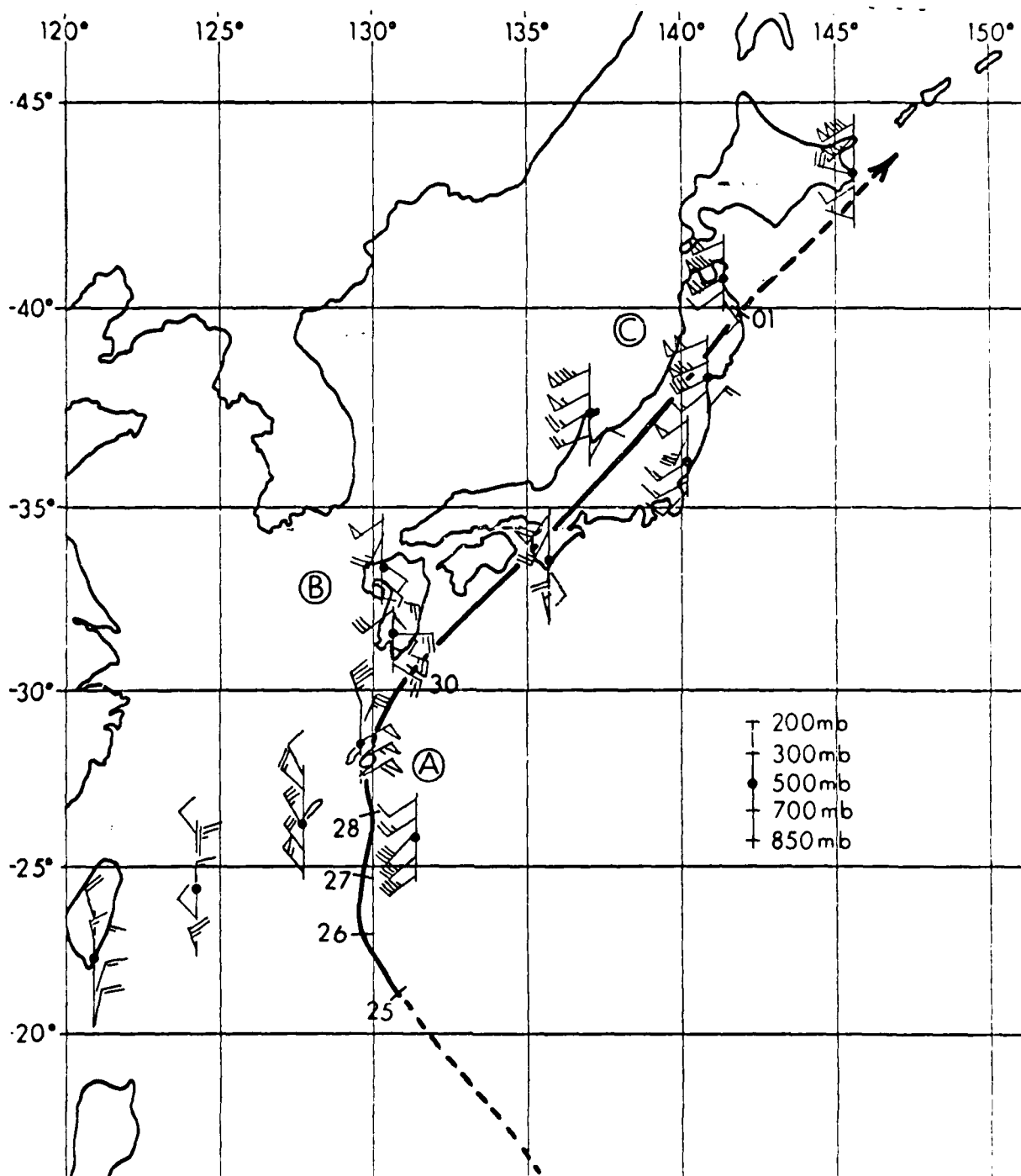


Fig. 11. Vertical wind profiles at 00Z on 29 September 1979 for observing stations close to track of Typhoon Owen. Data levels are from 850 to 200 mb as indicated on the ladder.

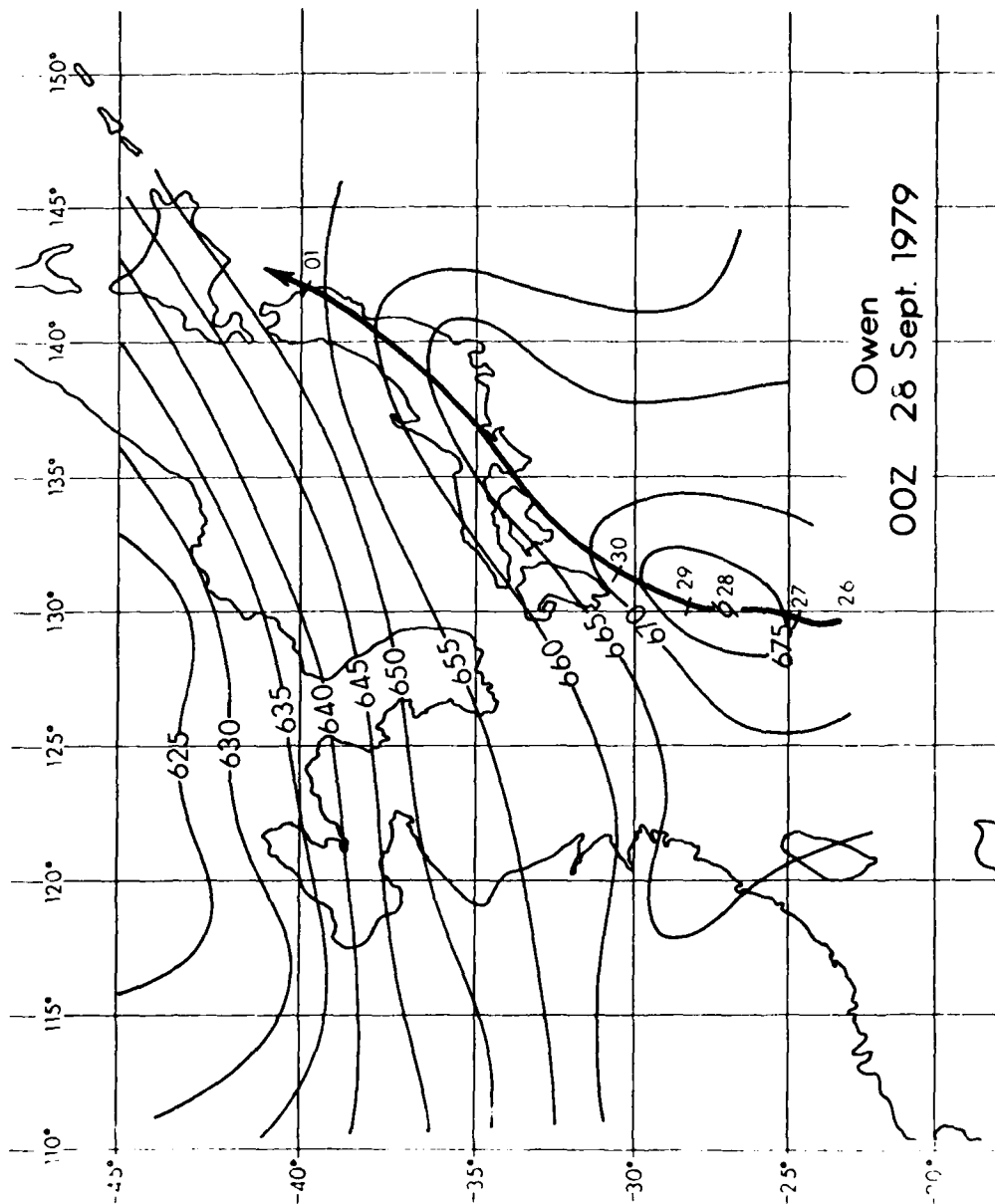


Fig. 12. 500 to 200 mb thickness analysis at 00Z on 28 September. Isolines labeled in tens of meters. Position of Typhoon Owen indicated by the storm symbol. Subsequent track shown by heavy solid line.

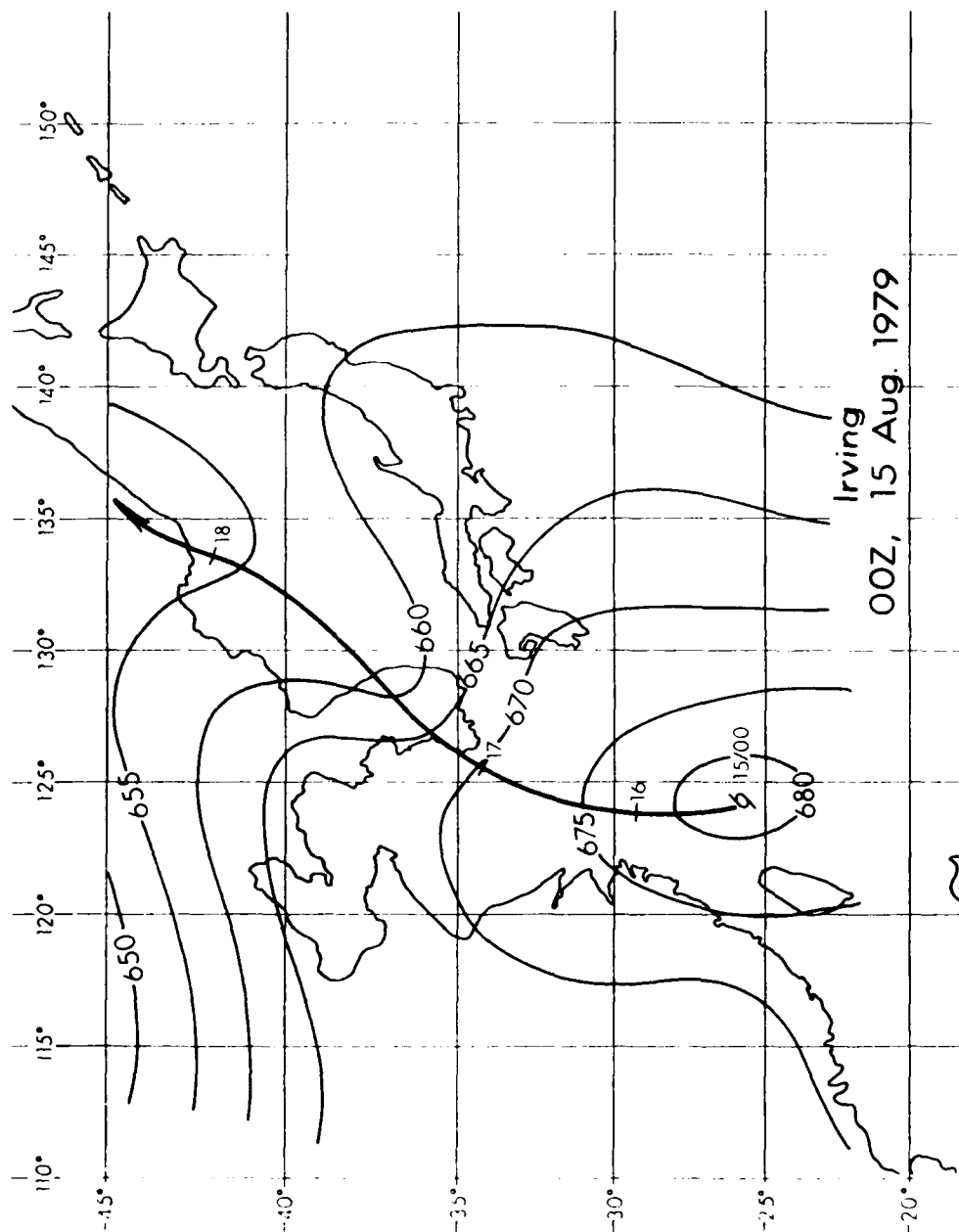


Fig. 13. 500 to 200 mb thickness analysis at 00Z on 15 August. Isolines labeled in tens of meters. Position of Typhoon Irving indicated by the storm symbol. Subsequent track shown by heavy solid line.

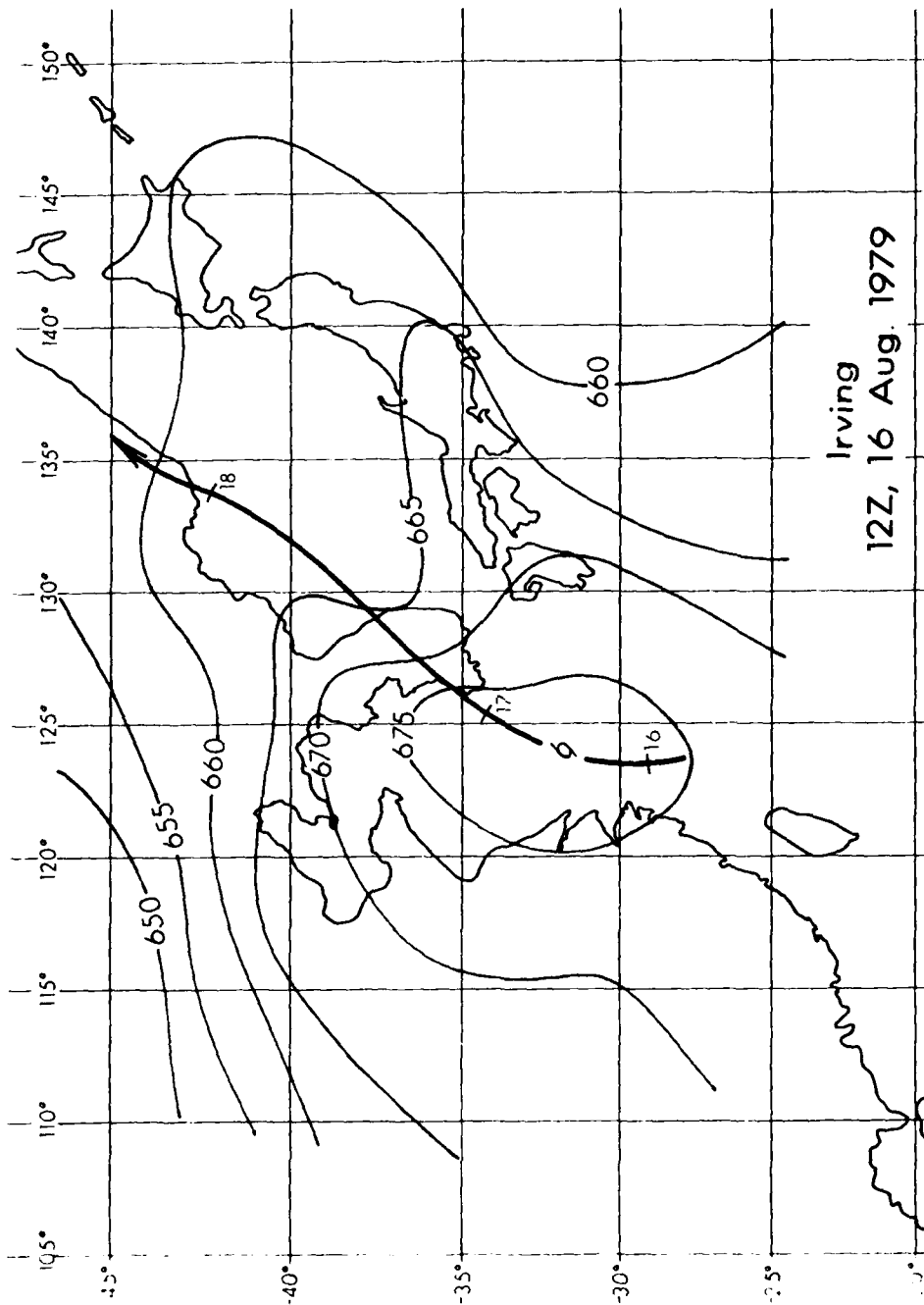


Fig. 14. 500 to 200 mb thickness analysis at 12Z on 16 August. Isolines labeled in tens of meters. Position of Typhoon Irving indicated by the storm symbol. Subsequent track shown by heavy solid line.

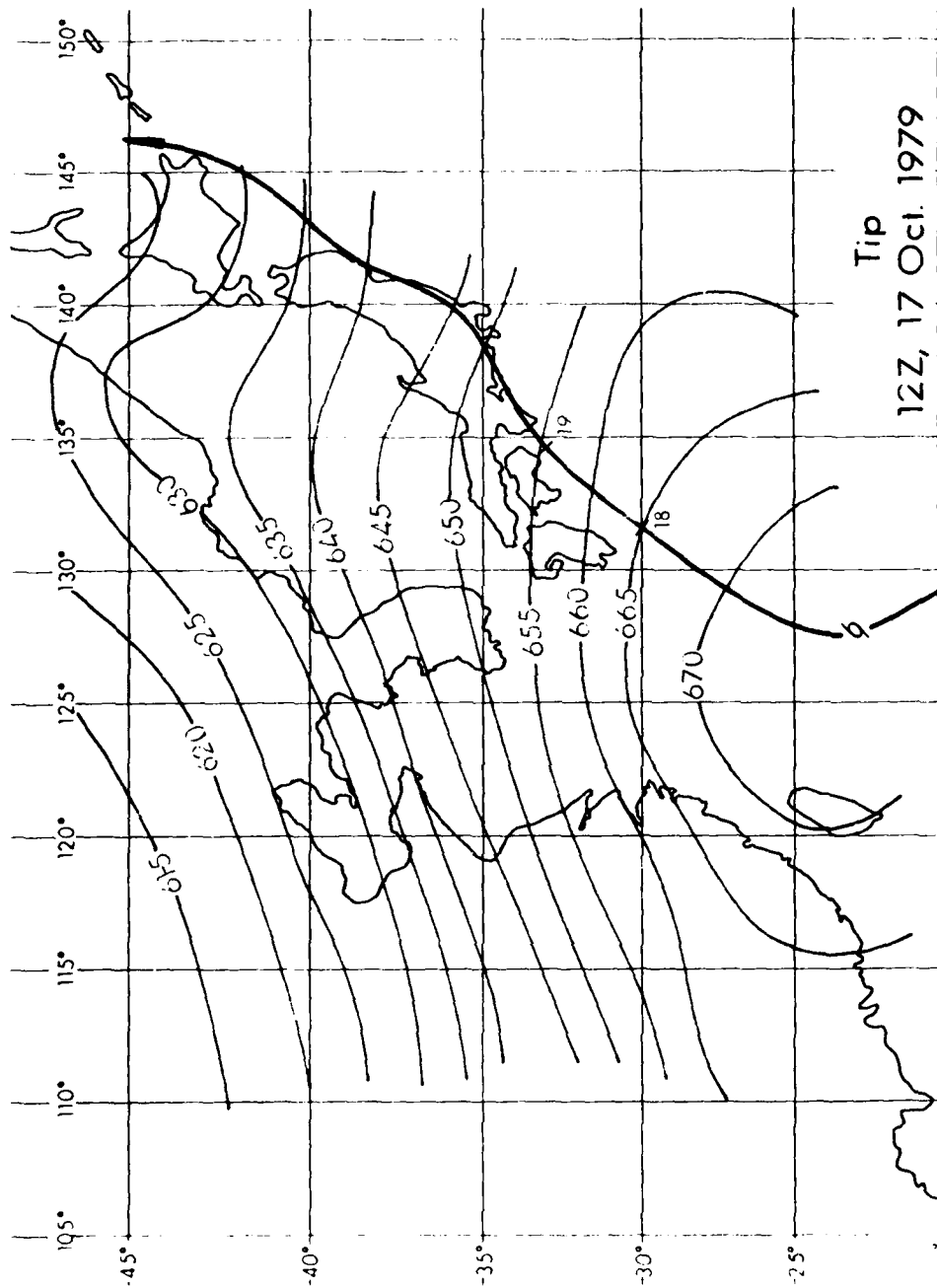
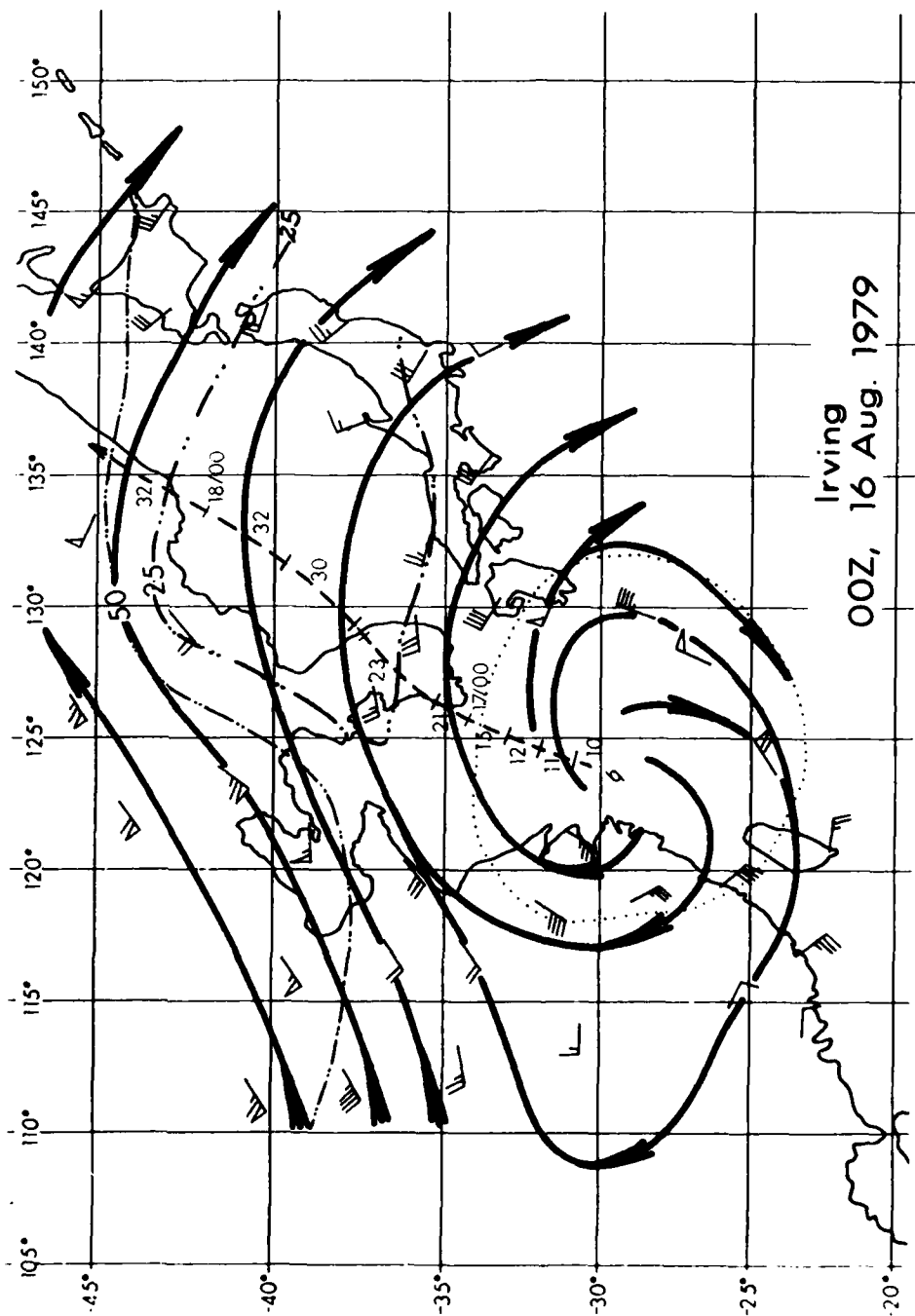


Fig. 15. 500 to 200 thickness analysis at 12Z on 17 October. Isolines labeled in tens of meters. Position of Typhoon Tip indicated by storm symbol. Subsequent track shown by heavy solid line.



Irving
00Z, 16 Aug. 1979

Fig. 16. Analysis of vertical wind shear (kt) between 850 and 200 mb at 00Z on 16 August. Area dominated by Typhoon Irving circulation is within dotted circle. Dashed line is subsequent typhoon track. Typhoon movement speed (kt) shown in 6 hr segments along track.

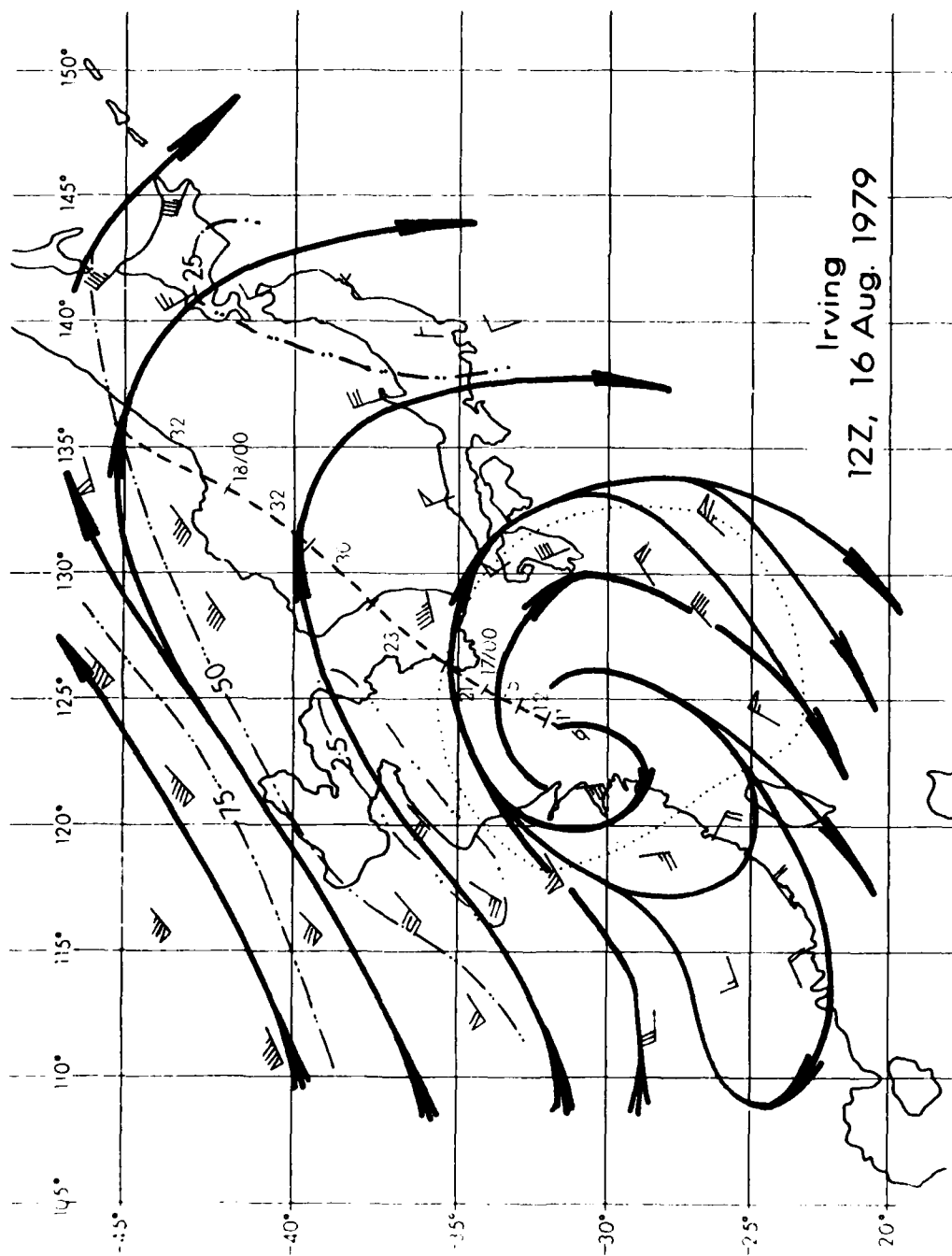


Fig. 17. Same as Fig. 16 except for Typhoon Irving at 12Z on 16 August.

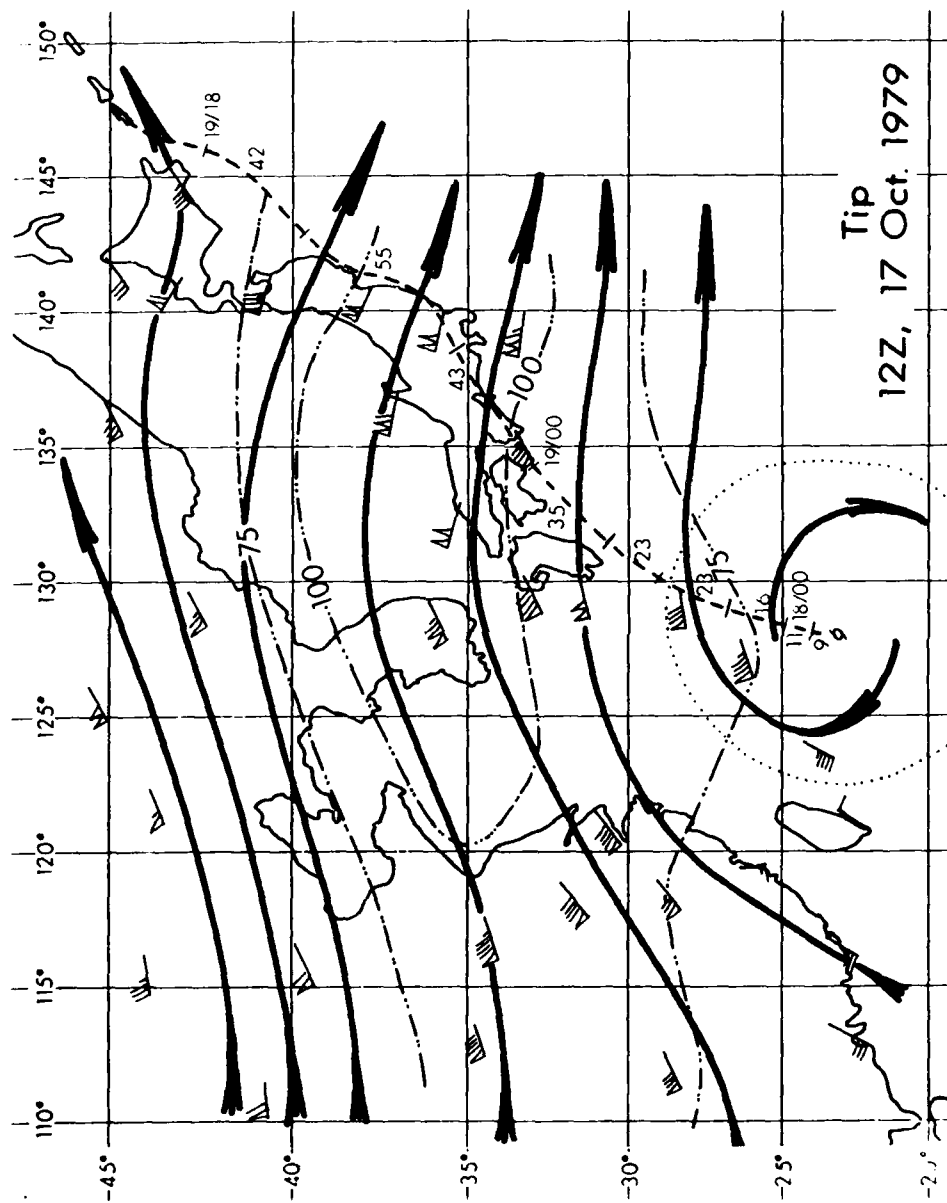


Fig. 20. Same as Fig. 16 except for Typhoon Tip at 12Z on 17 October.

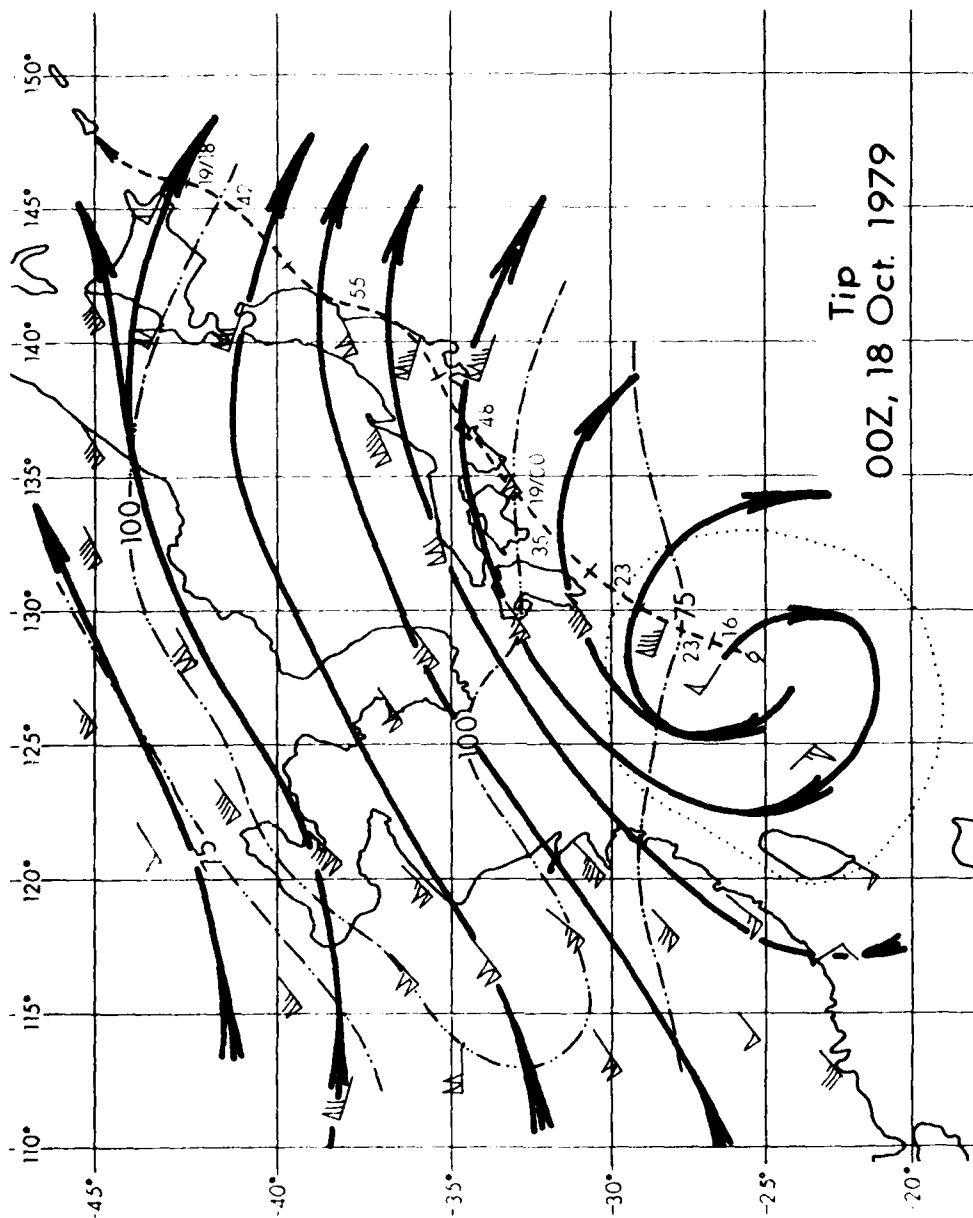


Fig. 21. Same as Fig. 16 except for Typhoon Tip at 00Z on 18 October.

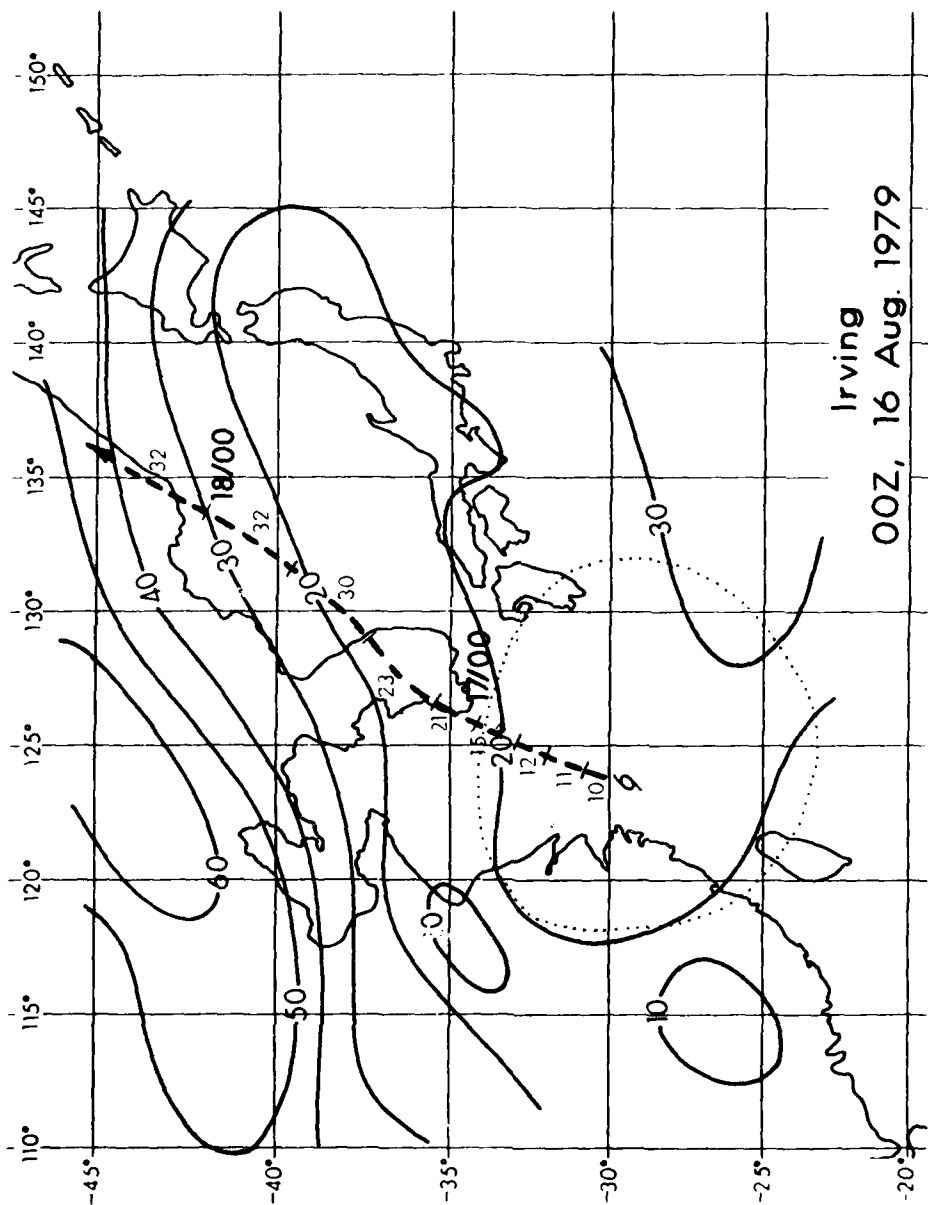


Fig. 22. An analysis of the averaged wind speed (kt) between 500 and 200 mb at 00Z on 16 August. Area directly influenced by Typhoon Irving is within dotted circle. Dashed line is subsequent typhoon track. Typhoon movement speed (kt) is shown in 6 hr segments along track.

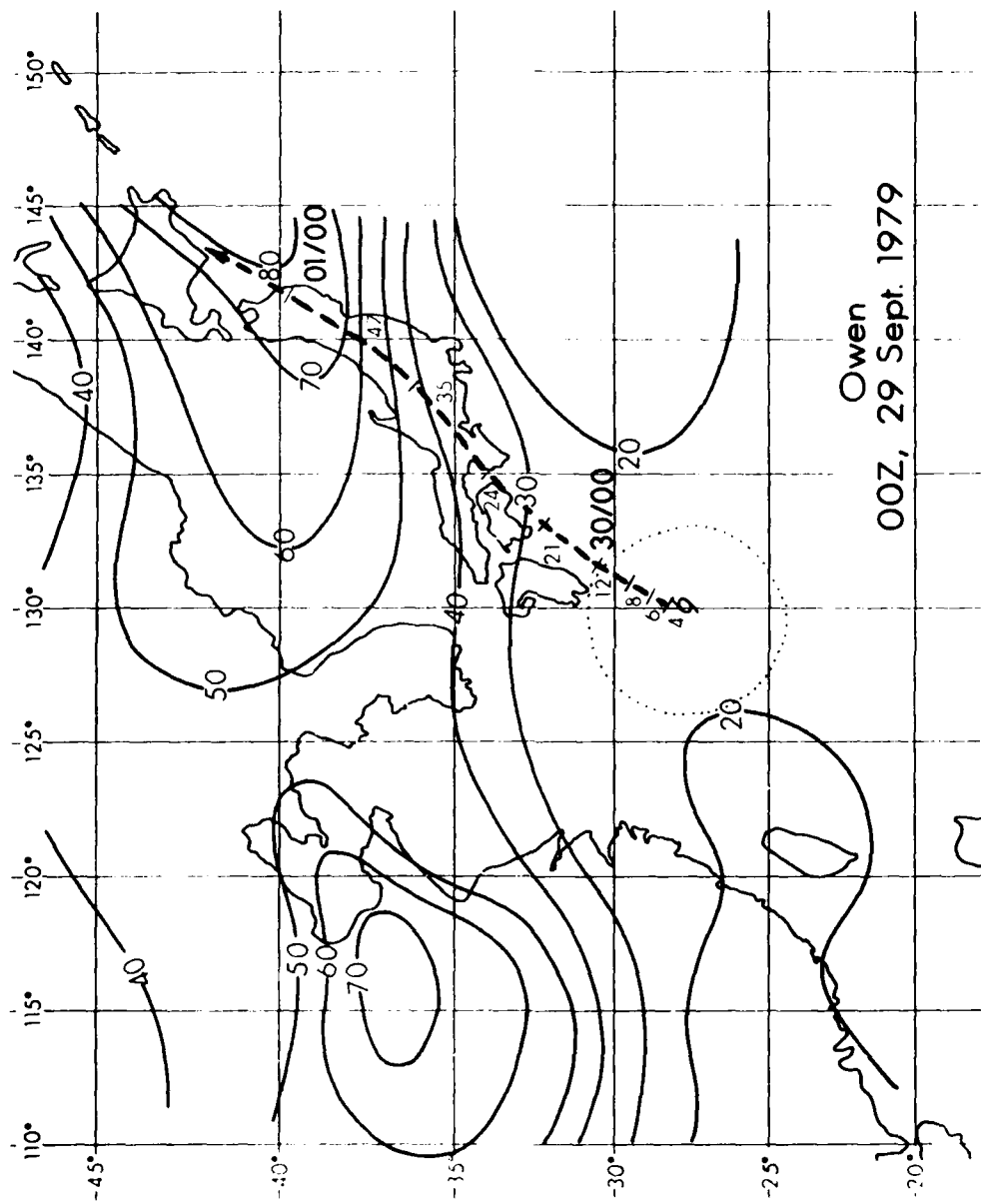


Fig. 23. Same as Fig. 22 except for Typhoon Owen at 00Z on 29 September.

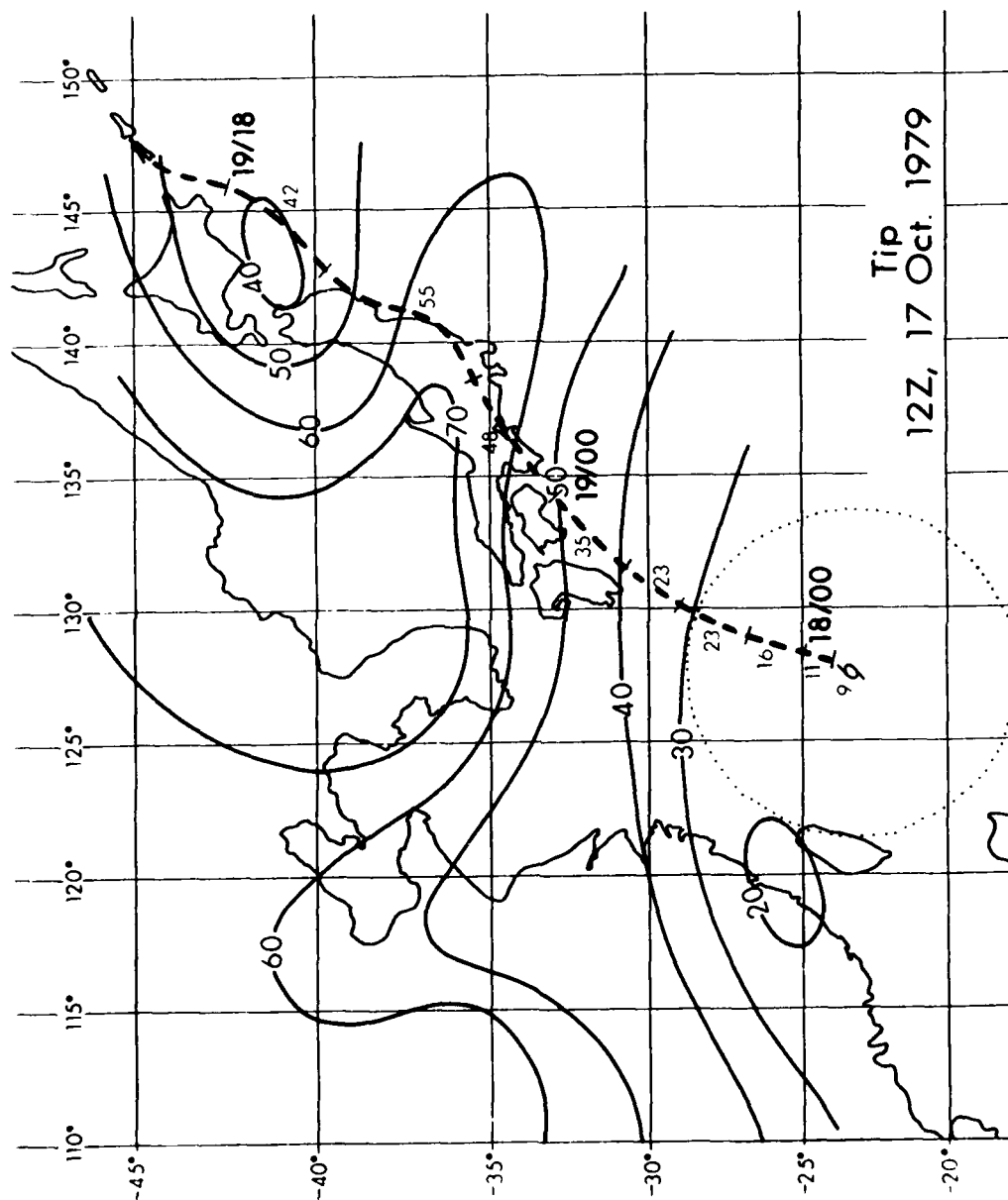


Fig. 24. Same as Fig. 22 except for Typhoon Tip at 12Z on 17 October.

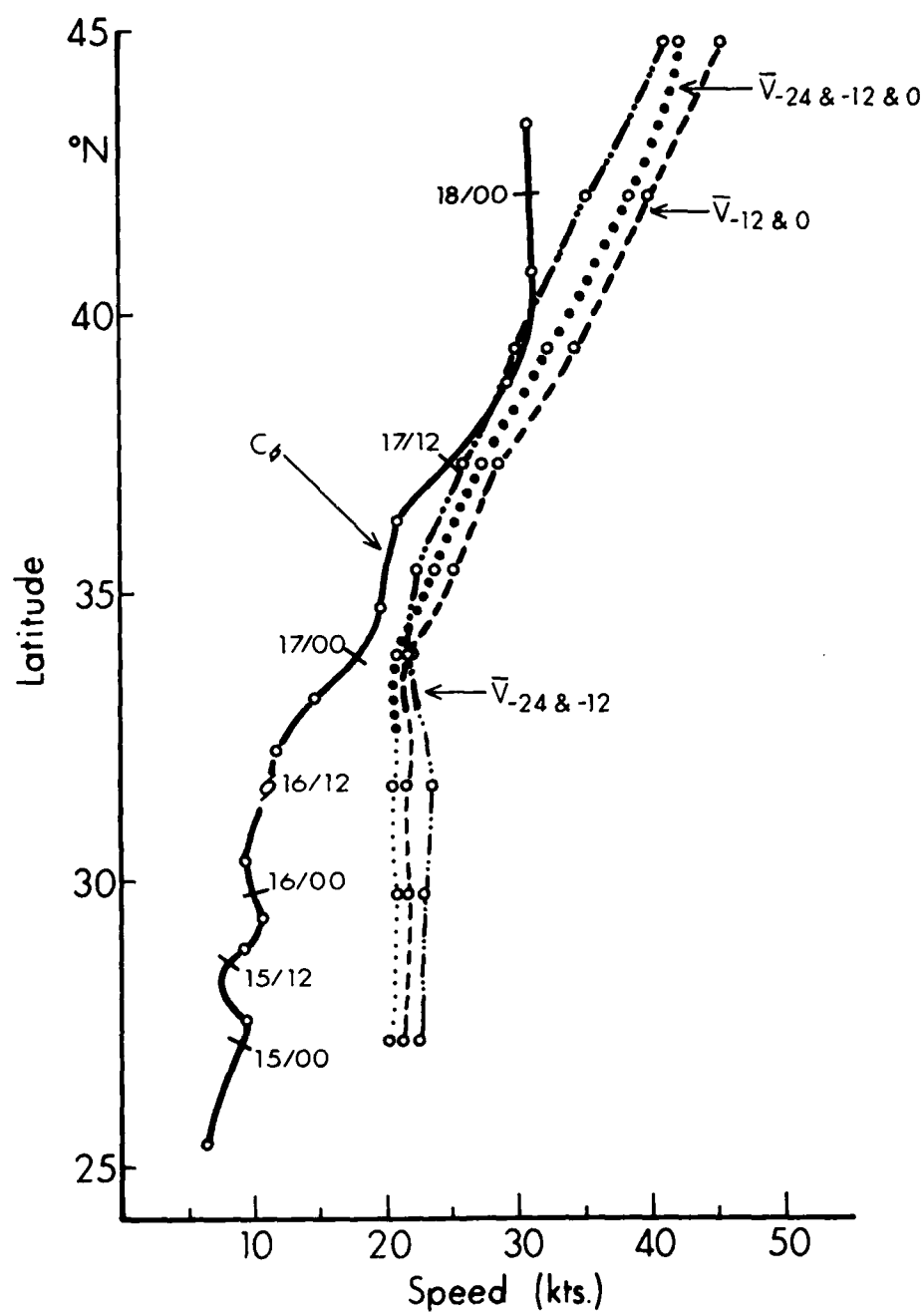


Fig. 25. Plot of moving speed of Typhoon Irving (c) and the averaged wind speed between 500 and 200 mb (\bar{v}) along the typhoon track averaged for the time periods indicated (hr) in relation to 12Z on 16 August as time 0.

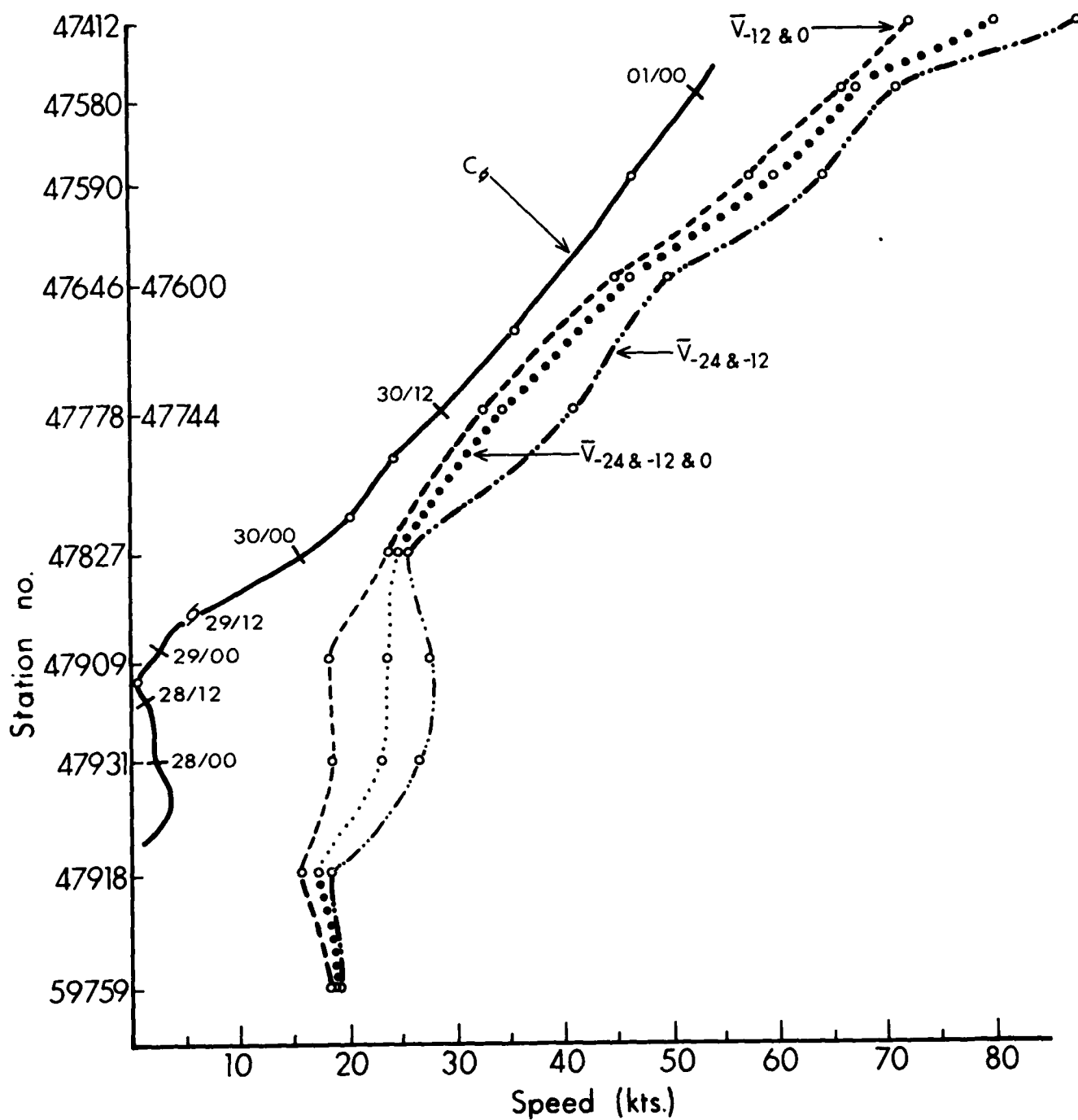


Fig. 26. Plot of moving speed of Typhoon Owen (c) and the averaged wind speed between 500 and 200 mb (\bar{v}) along the typhoon track averaged for the time periods indicated (hr) in relation to 12Z on 29 September as time 0. Wind observing stations along ordinate.

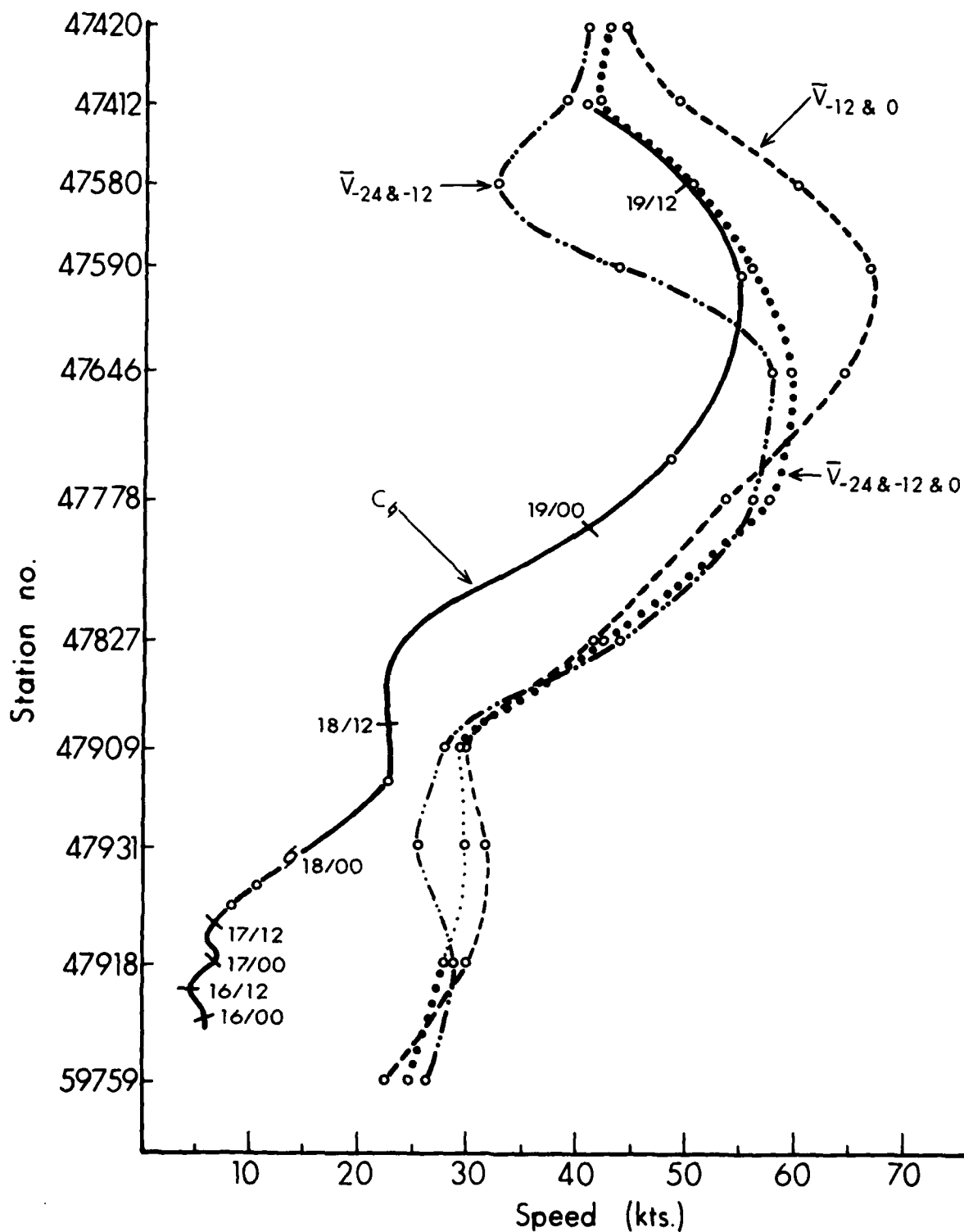


Fig. 27. Same as Fig. 26 except for Typhoon Tip and 00Z on 18 October as time 0.

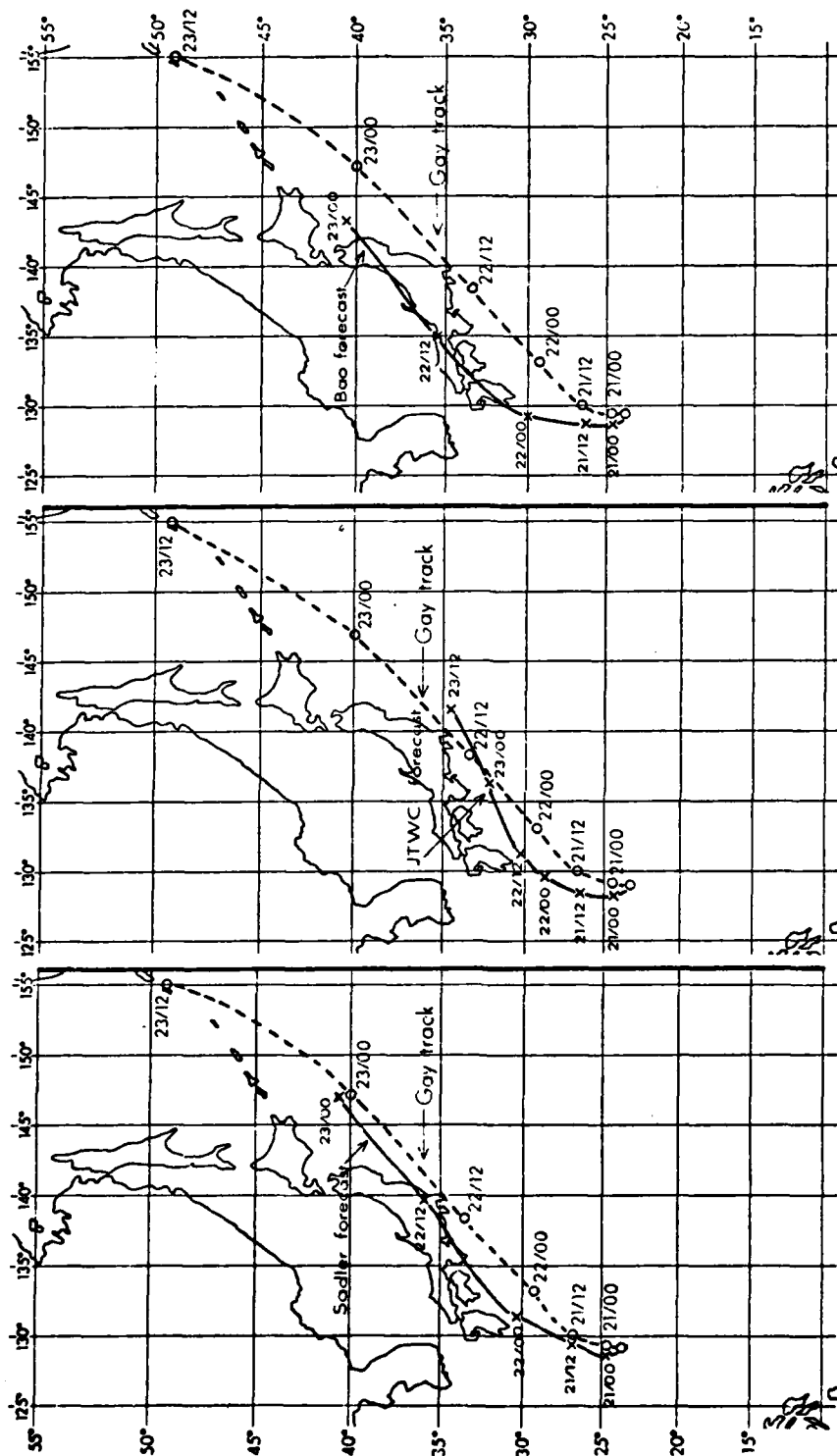


Fig. 28. Plots of Typhoon Gay's track and forecasts made at 12Z on 21 October 1981 by Bao, Sadler and JTWC.

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